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ABSTRACT

Investigations in Natural Science is a program in secondary school biology, chemistry, and physics based upon the description of science as a quest for knowledge, not the knowledge itself. This student manual contains the 36 physics investigations which focus on concepts related to: movement; vectors; falling objects; force and acceleration; a property of matter; mass and acceleration; laws of motion; circular motion; gravitational attraction; friction; the balance; the NBP (natural balance point); multiple forces; the lever; other machines; the inclined plane; energy; measuring heat; measuring heat in solids; circuits and currents; electrical circuits; electricity at rest; magnetism; currents and magnetism; light; light and plane mirrors; light and concave mirrors; refraction of light; light and converging lenses; waves; waves and barriers; speed of a wave; meeting waves; periodic wave relationships; sound; and harmonics. Each investigation (which is accompanied by one or more readings with questions to answer) includes activities related to the three learning cycle components, namely, exploration, conceptual invention (the idea), and expansion of the idea. (JN)

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INVESTIGATIONS IN NATURAL SCIENCE

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PHYSICS

Student Investigations and Readings

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TABLE OF CONTENTS

Investigation 1: Movement 1
  Reading: Moving Vehicles 15

Investigation 2: Vectors 25
  Reading A: Force 35
  Reading B: Vectors and Motion 37

Investigation 3: Falling Objects 39
  Reading A: Aristotelian Physics 57
  Reading B: Bodies in Motion 58
  Reading C: Galileo vs. Aristotle 61
  Reading D: Double Trouble 62

Investigation 4: Force and Acceleration 66
  Reading: Forces and Accelerations 75

Investigation 5: A Property of Matter 80
  Reading: Mass--Not a Weighty Matter 89

Investigation 6: Mass and Acceleration 91
  Reading: Mass and Acceleration 96

Investigation 7: The Laws of Motion 97
  Reading A: Isaac Newton 112
  Reading B: Laws of Motion 115
  Reading C: Rockets 118
  Reading D: Mass vs. Weight 120

Investigation 8: Circular Motion 122
  Reading A: Centripetal vs. Centrifugal Force 140
  Reading B: Frames of Reference 143
  Reading C: Circular Motion 144
  Reading D: Freefall Forever 145
  Reading E: An Attractive Law 153

Investigation 9: Gravitational Attraction 160

Investigation 10: Friction 173
  Reading: Friction, Friction, Everywhere 192

Investigation 11: The Balance 195
  Reading: Weight or Mass? A Balanced View 201

Investigation 12: Studying the NBP 203
  Reading A: Archimedes--I Can Move the World 210
  Reading B: Down and the Center of Gravity 215

Investigation 13: Multiple Forces 225
  Reading: Torque Around You 235

Investigation 14: The Lever 237
- Reading: Work and Energy Measurement 242

Investigation 15: Other Machines 247
- Reading A: Machines 257
- Reading B: The Wheel and Axle 264

Investigation 16: The Inclined Plane 266
- Reading: Using the Inclined Plane 274

Investigation 17: Energy 278
- Reading A: Energy 287
- Reading B: Two Energy Sources 295

Investigation 18: Measuring Heat 299
- Reading A: The Mechanical Equivalent of Heat 310
- Reading B: Conservation of Energy 315

Investigation 19: Measuring Heat in Solids 322
- Reading: Conduction and Convection--A Heated Exchange [illegible]

Investigation 20: Circuits and Currents 337
- Reading: Circuits 347

Investigation 21: Electrical Charges 349
- Reading A: Ampere, Ohm, and Volta 373
- Reading B: Using Circuits 376
- Reading C: Viva La Resistance 383

Investigation 22: Electricity at Rest 386
- Reading A: Edison's Experiment 401
- Reading B: Electric Potential Difference 404
- Reading C: The Electrical Force-Distance Law 408

Investigation 22A: Electricity at Rest 411

Investigation 23: Magnetism 421
- Reading A: The Earth as a Magnet 429
- Reading B: Earth's Magnetic Field 431
- Reading C: Magnets and Magnetic Fields 433

Investigation 24: Currents and Magnetism 435
- Reading: Magnets 447

Investigation 25: Light 454
- Reading A: Solar Energy 459
- Reading B: The Photoelectric Effect 461

Investigation 26: Light and Plane Mirrors 465
- Reading A: Front-Surface Mirrors 471
- Reading B: A Plane, But Not Dull Story 472

Investigation 27: Light and Concave Mirrors 474
Reading A: Two Parabolic Headlights is Not the Same as Four Bolic Headlights 494
Reading B: Other Parabolic Reflectors 496

Investigation 28: Refraction of Light 498
Reading: Tall Stars and Mirages 508

Investigation 29: Light and Converging Lenses 510
Reading A: Eye See! 519
Reading B: Camera See, Monkey Do 524

Investigation 30: Waves 530
Reading: Energy From Ocean Waves 534

Investigation 31: Waves and Barriers 535
Reading: Other Waves 551

Investigation 32: Speed of a Wave 555
Reading: The Medium for Light 561

Investigation 33: Meeting Waves 564
Reading: A Wavelength for Light 576

Investigation 34: Periodic Wave Relationships 586
Reading: Colors 593

Investigation 35: Sound 597
Reading A: Organic Music 604
Reading B: Harmful Resonances and Sound Reflection 605

Investigation 36: Harmonics 610
Reading: Musical Scales 613

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INVESTIGATION 1: MOVEMENT STUDENT GUIDE

Name____________________

Section____________________

Introduction

A race car standing still on the starting line crosses the quarter mile finish line a few seconds after a starting signal is given. A flagged peg in a glacier is 20 feet away from the place it was inserted a year earlier. Both the race car and the glacier peg have moved. How are their motions alike? How can the movement of any object be described? This investigation will concentrate on leading you to be able to describe the different types of movements objects can have.

Exploration

Set up the equipment as shown in the diagram below.

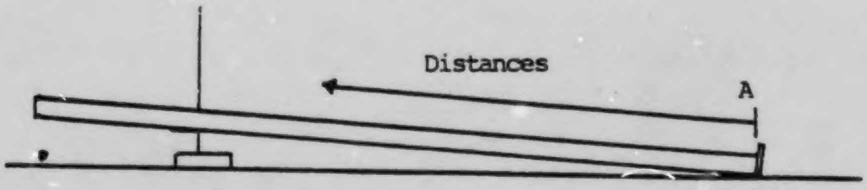

Figure 1

Use the ring stand and ring to raise one end of the track. Your teacher will tell you how much slope the track should have.

You will be varying distance. Place masking tape on the track at the following distances from point A: 25.0 cm, 50.0 cm, 75.0 cm, 100.0 cm, 125.0 cm, 150.0 cm, and 175.0 cm. These distances will be recorded in Table I. Next, you will measure the time required for the ball to travel each of those seven distances.

1. Begin taking data by placing the ball at the 25.0 cm mark. To start the ball the same way each time, keep it at the mark on the incline with a pencil until you are ready to release it and begin timing. Start the stopwatch as the ball is released and stop the watch as the ball reaches the stop. Let more than one person read the stopwatch to prevent reading errors. Make three measurements of time to as many decimal places as possible. Record those values in the space provided.

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2. Gather the same data as before, but start the ball at the mark that will make the distance equal to 50.0 cm. Make three measurements of time, record and average them in Table I.

3. Repeat the data gathering process for each of the other distances. Record the data as with the other distances in Table I.

Table I

Trial	Distance	Time (sec)	Average	
1				
2				
3				
4				
5				
6				
7				

In the space below, write a summary of the data you have just recorded in Table I.

The Idea

1. Make a graph of distance on the incline against time. Put distance on the vertical axis of the graph and time on the horizontal axis.

   a. What is the shape of the line on your graph?

   b. How does the distance change as the time increases?

   c. According to the graph, what was happening to the ball on the track?

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Name__________________________

Section________________________

Expansion of the Idea

Part 1: Problems

1. Dallas and Oklahoma City are about 200 road miles apart. How fast will a driver have to make his car move if he wants to make the trip in:

   a. 4 hours

   b. 3 hours

   c. 2 hours

   d. 1 hour

2. A runner in a 100 meter race passes the 40 meter mark with a speed of 10 m/sec.

   a. Where would you expect him to be three seconds later?

b. If he maintains his speed, what will be his time for the race?

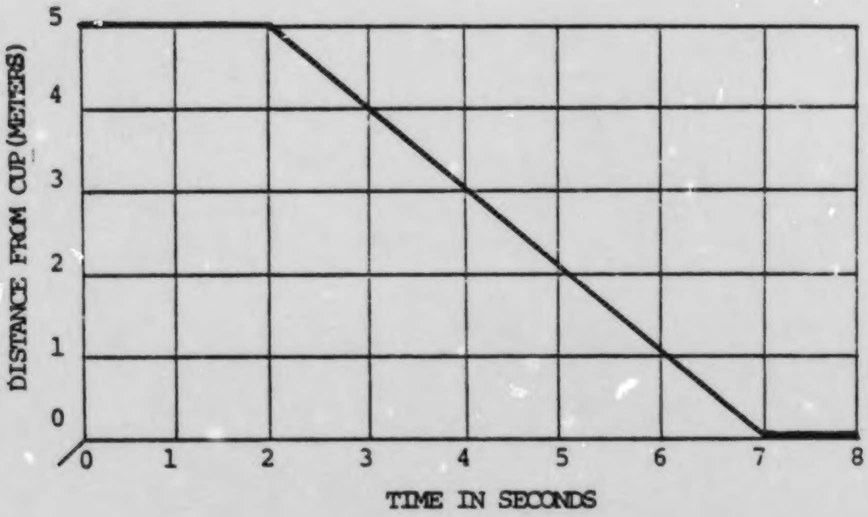

Figure 2

3. The graph above describes the motion of a golf ball. The ball is placed on the green at 5 meters from the cup at t=0 seconds.

a. How far from the cup was the ball at t=1 second?

b. What was the speed of the ball at t=1 second?

c. How far from the cup was the ball at t=5 seconds?

d. What was the speed of the ball as it moved toward the cup?

e. What happened at t=7 seconds?

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Name____________________

Section____________________

Expansion of the Idea

Part 2: Acceleration

In the empty column of Table I, determine the speed (v) of the ball in each trial. Make a graph of speed (in cm/sec) against time (in seconds). This way we can easily see how the speed is changing with time. Put the speed on the vertical axis, and time on the horizontal axis. Be sure to label the axes clearly.

1. What would be the speed of the ball if the time we allowed for the ball to move were 0 sec?

2. Is the point (0,0), a point on the line?

Make a smooth (unjagged) line that represents the apparent relationship between the speed and time. The lines does not have to go through all the points. The points are averages and the actual measurements may vary somewhat, but the line should show how the points are arranged on the graph.

3. What kind of line do you get? (Is it straight or curved?)

INVESTIGATION 1: MOVEMENT

STUDENT GUIDE

Name ______________________

Section ______________________

Expansion of the Idea

Part 3: Experimentation and Interpretation of the Data

1. A moving ball is slowing down. Explain why it has acceleration.

____

____

2. What would be the acceleration of a ball that is on a level track moving at a constant speed? Explain.

____

____

3. How would increasing the incline of the track affect the acceleration of the ball?

____

____

To find out if you have answered Question 3 correctly, change the angle of the track and gather data that will allow you to determine the acceleration. You will need the time of travel of the ball for at least four distances. Record your data in Table II. Graph the data as you did in Part 2.

Table II

Trial	Distance	Time (sec)	Average	V_{Avg}	V_f
1					
2					
3					
4					

4. How did the incline of the first track in the Exploration section compare with the incline of the second track?

____

____

5. How did the acceleration of the ball on the second incline compare with the acceleration on the first incline?

____

____

6. How did the slope of the line in the graph for the Expansion of the Idea section, Part 2, compare with the slope of the line in the graph you just constructed?

____

____

7. What is the relationship between the slope of the line of the graph of speed vs. time and the acceleration?

____

____

8. A car starts at rest and accelerates to 60 miles per hour in 10 seconds. What is its average acceleration?

____

____

9. A bowling ball dropped from the top of the Empire State Building reaches a speed of 24.5 m/sec in 2.5 seconds. What is its acceleration?

____

____

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Name ______________________

Section ______________________

Expansion of the Idea

Part 4: Combining the Variables of Motion

Using the three equations we wrote for velocity and acceleration (that is, $v=d/t$, $v=v_f+v_i/2$, and $a=v_f-v_i/t$), figure out ways to combine them algebraically to make five other equations that would enable you to:

1. Solve for v_f when you know v_i, a, and t.

2. Solve for d when you know v_i, a, and t.

3. Solve for a when you know v_i, d, and t.

4. Solve for t when you know d and a, and $v_i=0$.

5. Solve for v_f when you know v_i, a, and d.

Name ____________________

Section ____________________

Expansion of the Idea

Part 5: Acceleration Problems

Always put your answers in decimal form, not fractions.

1. A fly takes off with an acceleration of 0.70 m/sec^2 from a wall. How long will it take the fly to reach a speed of 3.5 m/sec?

2. A cart rolling down an incline passes a point A moving at a rate of 2 m/sec. It is accelerating at a rate of 3 m/sec^2.

   a. How fast is it moving when it passes point B ten seconds later?

   b. How far is point B from point A?

3. A car starts from rest and accelerates uniformly for 30 seconds. During that time, its average velocity is 0.50 meters per second. What is its acceleration?

Name____________________

Section____________________

Expansion of the Idea

Part 6: Questions on the Reading

1. What are the units of the slope of a distance vs. time graph?

____

2. What name has been given to the slope of a distance vs. time graph?

____

3. a. Describe two ways to determine average speed given in the reading. (You may use equation form to answer this question if you choose.)

____

____

b. What assumptions about acceleration are involved in each method?

____

____

____

4. What are the units of the slope of a speed vs. time graph?

____

5. What name has been given to the slope of a speed vs. time graph?

____

6. a. According to the reading, what is acceleration?

   ____

   ____

   b. What are the units of acceleration?

   ____

   c. How does km/sec/sec compare with km/sec^2?

   ____

   ____

   d. Why might some people prefer to use km/sec/sec?

   ____

   ____

   e. Why might some people prefer to use km/sec^2?

   ____

   ____

7. What is the purpose of the discussion on Pages R1-7 and R1-8 involving Tables R1-3 and R1-4 and Figure R1-3?

   ____

   ____

   ____

8. Explain why, in determining the average acceleration from the graph in Figure R1-3, the acceleration during the first interval is added three times.

   ____

   ____

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9. How is the acceleration in Figure R1-4 different from the acceleration in Figure R1-2?

10. What is meant by negative acceleration, or deceleration?

INVESTIGATION 1: MOVEMENT

READING: MOVING VEHICLES

You are probably familiar with the speedometer of a vehicle. It tells you several things. You can find out how far the vehicle has traveled since it was manufactured. That part of the speedometer is called the *odometer*. Some speedometers have as a part of the speedometer an odometer that will only read 999.9 miles. That is often called a *trip odometer*.

The principal portion of the speedometer tells you how fast you are going. If the vehicle has been manufactured in the United States or is for sale in that country, the speedometer measurer is in miles per hour. In many other countries the speedometer measures kilometers per hour.

The word *meter* means measure. So a speedometer is a device that measures speed. Now speed is a rate. It tells how much distance is covered in a specific amount of time. Well, that's not entirely true. The speedometer really tells you how far you would travel in one hour if you maintained the speed you have *at that instant*. An instant later, that speed may be different. So what the speedometer really tells you is your *instantaneous* speed.

Table I

Distance (meter)	Time (seconds)
10	2
20	4
40	8
60	12
70	14
80	16

Study the data in Table I. Those data represent the distance a moving object travels in sixteen seconds. For example, the object traveled 10 meters the first two seconds it moved.

The data from Table I have been plotted on the graph in Figure 1. That graph provides an excellent definition of speed. Notice that as the distance kept increasing, time kept passing.

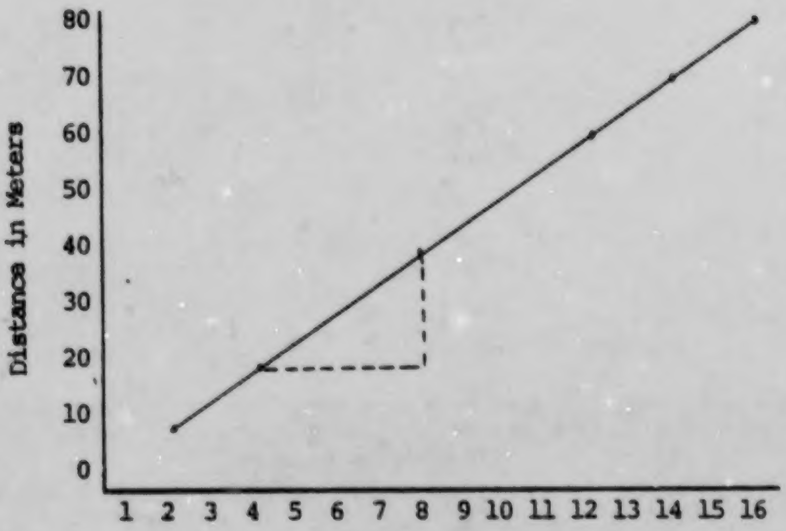

Figure 1

A horizontal line has been drawn from the 20 meter and 4 second point on the graph. A vertical line has been dropped from the 40 meter and 8 second points. Study that small triangle. Notice that its altitude is 20 meters and its base is 4 seconds. The slope (m) of the hypotenuse of that triangle is:

$m=20\ m/4\ sec=5\ m/sec$

The slope tells us that the moving object travels 5 meters in one second. Now the number of meters an object moves in one second is its speed. The units of speed are those of distance and time.

Suppose you find the slope of the line between 50 meters and 80 meters and the beginning and end of the measurement. Those values are:

$m_{80-50}=30\ m/6\ sec=5\ m/sec$

$m_{0-80}=80\ m/16\ sec=5\ m/sec$

INVESTIGATION 1: MOVEMENT

Those slopes tell you that the speed throughout the 16 second measured-time interval is always the same. You may think about any two points in the interval or the entire interval; the speed is always the same. When speed is the same throughout an interval, it is called constant speed.

Suppose you are traveling down the road with an instantaneous speed of 50 miles per hour. You travel on for ten minutes before you look at the speedometer again. You are now traveling 56 miles per hour. What is your average speed over that ten-minute period? You have two measurements of your speed. You know how to find an average of any item. You add all the values you have together and divide by the number you have. So your average for the ten-minute interval is 50 miles per hour plus 56 miles per hour divided by two.

$$\text{Or average speed} = \frac{(50+56)}{2} \text{ miles per hour} = 53 \text{ miles/hr.}$$

So average speed ($\bar{v}$) is an average of instantaneous speeds over a specific time interval. When some one says they averaged 55 miles per hour on a 500 mile trip, they probably did not use instantaneous speeds. They probably divided the total distance they traveled by the total amount of time required. That equation is very useful. It is:

$d=\bar{v}t$, d=distance traveled

$\bar{v}$=average speed

t=time required to travel the distance d

From the equation $d=\bar{v}t$, the quantity $\bar{v}$ can be studied. Rewrite the equation to read $\bar{v}=d/t$. In other words, speed is measured in units of distance and time. Any units of distance and time will give you speed. For example, the distance from the earth to the sun is 93,000,000 (93×10^6) miles. The earth travels in a nearly circular orbit about the sun. That orbit is slightly elliptical, but for our purposes, consider it a circle. The radius, R, of the circle is 93×10^6 miles. The distance, d, the earth travels each year is $d=2 \quad R=2\times3.1493 \;\times10^6=58.4\times10^7$ miles. The average speed of the earth in its orbit is v=d/t(miles per day). Or:

$$\bar{v} = \frac{58.4\times10^7 \text{ miles}}{365 \text{ days}}$$

$$\bar{v} = \frac{58.4\times10^7 \text{ miles}}{365 \text{ days}\times24 \text{ hour/day}} = 6.67\times10^4 \text{ miles/hour}$$

Any of those units is an acceptable set to use to measure speed. Geologists measure the speed of a glacier in centimeters per year.

All of the discussion in the last paragraph focused upon average speed. Earlier you read that average speed was found by averaging instantaneous speeds. To really understand instantaneous speed you need to understand what is meant by an instant. The dictionary defines instant as a very brief time, a moment, immediate. All of those definitions are true, but they are still too long to accurately understand instantaneous velocity. Imagine that you are standing at a particular point on the Indianapolis Speedway. Cars there probably travel the fastest of any place in the world. You hold a speed measurer in your hand. No need to worry about how it works; it is just a black box that measures speed. A car comes roaring at you and flashes by in a very tiny part of a second. Your speed measurer tells you how fast the car is going. That is probably as close as you can come to measuring instantaneous velocity.

The radar devices used by police to measure the speed of moving cars also measure instantaneous speed. Little value will come from trying to convince a police officer that your average speed was below the limit. The officer's radar device has read your instantaneous speed at that moment when you were above the speed limit. The fact that you were below the speed limit earlier might bring your average speed below the speed limit, but doesn't interest the officer. Your speeding ticket will reflect only your instantaneous speed.

Speed is measured in distance per unit of time. Kilometers per hour (km/hr) really tell you that the unit of distance measured is the kilometer and the unit of time is the hour. A speed of 90 kilometers per hour tells you that the moving object traveled 90 kilometers in one hour.

INVESTIGATION 1: MOVEMENT

A car has an instantaneous speed of 90 Km/hr. The next measure of its instantaneous speed was taken 10 minutes later and it was 80 km/hr. In other words, the change in the speed of the car was 10 km/hr during 10 minutes. Or:

$$\text{Change of speed} = \frac{90 \text{ km/hr} - 80 \text{ km/hr}}{10 \text{ minutes}}$$

To do much with that equation, the times measured must be all in the same units--minutes and hours don't mix. There are 60 minutes in one hour. The instantaneous speeds can be expressed in km/minute by simply dividing by 60 minutes. Or:

$$\frac{90 \text{ Km/hr}}{60 \text{ min/hr}} = 1.5 \text{km/min}$$

$$\frac{80 \text{ km/hr}}{60 \text{ min/hr}} = 1.3 \text{ km/min}$$

So the change of speed in 10 minutes (min) is:

$$\text{change of speed} = \frac{1.5 \text{ Km/min} - 1.3 \text{ Km/min}}{10 \text{ minutes}}$$

$$\text{change of speed} = \frac{0.02 \text{ Km/min}}{10 \text{ minutes}}$$

$$\text{change of speed} = 0.02 \text{ Km per min per min}$$

Notice the units of measurement in the change of speed. Those units are km per minute--which is speed--per minute. In other words, the change of speed takes place during a period of time. That could be said to be change of speed per unit of time--or Kms per minute per minute. Change of speed per unit of time is called acceleration and is measured in units of speed change per unit of time. Or:

INVESTIGATION 1: MOVEMENT

$$\text{acceleration (a)} = \frac{\text{change of speed}}{\text{Time}}$$

$$a = (v_1 - v_1)/\text{time} = \text{km/sec/sec}$$

But those aren't the only units in which acceleration can be measured. Speed can be measured in any units of distance and time. Acceleration then can be measured in any units of speed and time. Kilometers per week per year is as good a set of units for acceleration as are kilometer per second per second.

Look at the data in Table II. Those data represent the change in speed of an automobile starting out from rest. The data have been plotted on a linear graph in Figure 2.

Table 2

Speed (mi/hr)	Time (sec)
0	0
10	2
20	4
30	6
40	8

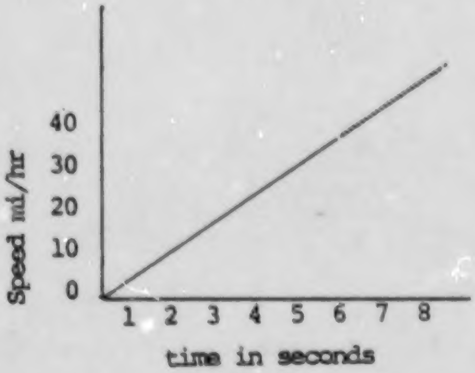

Figure 2

The line is straight. The slope, m, of a line like that shown in Figure 2 is:

$$m = (y_2 - y_1)(x_2 - x_1)$$

In Figure 2, y=speed and X=time. So the slope is:

$$m = (v_2 - v_1)/\triangle t = \text{change in time or time elapsed}$$

INVESTIGATION 1: MOVEMENT

Suppose we think about the interval between 10 miles/hr and 30 miles/hr. So, v_1=10 mi/hr, v_2=30 mi/hr, and $\triangle t$=4 sec. Thus:

$$m = \frac{(30-10)\text{ mi/hr}}{4\text{ seconds}} = 5\text{ mi/hr/sec}$$

The slope of the line has units. Those units, miles/hour/second, are the units of acceleration. The slope of a speed-time graph, therefore, will always give you acceleration.

In the speed-time graph you just studied, the increase in speed was very regular. Notice that if you compute the slope of the line between any two points, that slope has the same value. The physicist would interpret those data as meaning the acceleration is constant.

Now look at the data in Table III, and the graph of those data in Figure 3. Just looking at the graph tells you the acceleration is not constant.

Table III

Measurement	Speed (mi/hr)	Time (seconds)
0	0	0
1	10	3
2	20	4
3	30	6
4	60	7

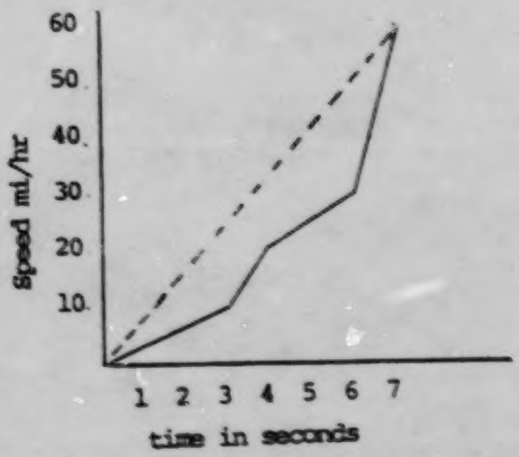

Figure 3

Acceleration changes between each two measurements. The solid line in the graph in Figure 3 is probably closer to what actually happens in acceleration than is the graph in Figure 2. Observe the data in Table IV. Notice how the slope changes from time interval to time interval. That simply means that the acceleration is changing during each time interval. What is the average acceleration during the seven second period?

Table IV

Interval	Time (sec)	Acceleration (mi/hr/sec)
0 to 1	3	3.3
1 to 2	1	10.0
2 to 3	2	5.0
3 to 4	2	30.0

The acceleration during the first time interval is 3.3 mi/hr/sec, but it goes on for 3 seconds. To give that acceleration its proper credit in the final average it must be added in three times. The next acceleration (10 mi/hr/sec) needs to be added into the total acceleration only once, the third acceleration (5 mi/hr/sec) is added in twice, and the last acceleration (30 mi/hr/sec) is added in only once. So:

$$A_{avg} = \frac{(3.3+3.3+3.3+10+5+5+30)\ \text{mi/hr/sec}}{7}$$

$$= \frac{59.9\ \text{mi/hr/sec}}{7}$$

$$= 8.5\ \text{mi/hr/sec}$$

Now look at the dotted line in Figure 3. The slope of that line equals the acceleration between the beginning and end of the seven-second interval. That slope is:

$$m = a = \frac{60\ \text{mi/hr} - 0\ \text{mi/hr}}{7\ \text{seconds}}$$

$$= 8.5\ \text{mi/hr/sec}$$

So the average acceleration during any interval can be found by finding the slope of the line forming the beginning point and end point of that interval. That average acceleration can also be found by averaging the acceleration during each record of a time interval.

The data shown in Table 5 are plotted in Figure 4. Those data show that the moving object is slowing down. The speed is changing so you know the object is accelerating. You know that the slope of a speed-time curve provides that acceleration. You also know that the equation used to compute that slope is:

$$m=a=(v_2-v_1)/\triangle t$$

Table V

Speed (mi/hr)	Time (seconds)
50	0
40	2
30	4
20	6
10	8

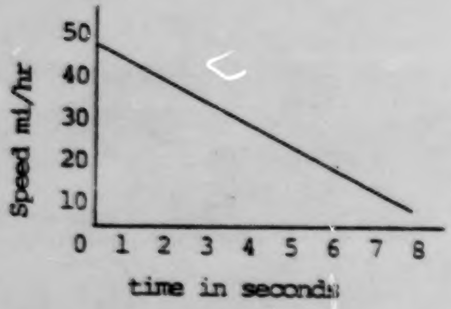

Figure 4

Now look carefully at the graph in Figure 3. Consider the acceleration in the time interval 2 seconds to 6 seconds where $v=40$ mi/hr, $v=20$ mi/hr, $\Delta t=4$ sec. So:

$$a = \frac{20 \text{ mi/hr} - 40 \text{ mi/hr}}{4 \text{ sec}}$$

$$= -5 \text{ mi/hr/sec}$$

Notice that the acceleration is negative. What does that mean? During that 4 second time interval the moving object slowed down. The negative sign, or negative acceleration, simply means that the moving object is slowing down. Negative acceleration is sometimes called deceleration.

Name________________________

Section________________________

Introduction

If you are told 4=4, you might reply, "What else could 4 equal besides 4?" Suppose you were told 3+4=5. Your reaction would probably be "Impossible!" Do not make that judgment too quickly. Remember you do not know the conditions under which 3+4=5. Perhaps the units 3, 4, and 5 are measured in are unusual. Maybe some other reason makes that impossible-looking situation possible. This experiment will permit you to investigate situations like 3+4=5.

Exploration

In this investigation you will work with forces. A force is a push or pull. Pick up a kilogram weight. What are the muscles in your hand and arm permitting you to do when you lift the weight? What do you do when you lift any object?

____

____

All objects have weight. Based upon your answers to the last two questions, how could you define weight?

____

____

Now hang the one kilogram weight on a spring scale. What does the spring scale measure?

____

____

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Instructions

The composition of forces apparatus (CFA) has three arms which can be adjusted to different angles. Each spring scale is attached to a ring in the center and to the end of one of the arms by string (see Figure 1). Each scale should be pulled tight enough so that it produces a reading. That reading is a force, F. (The scales show the size of each of the three forces.) Adjust the apparatus by changing the angle between its arms until the ring in the middle is centered. Notice how the readings on the scales change as you change the angle between any two of the arms of the CFA. Place the apparatus on top of a large piece of paper, keeping the ring centered. There are slots in the arms so that you can mark their exact locations on the paper. Record the scale reading next to the proper arm. These values will also be recorded under Trial 1, Table I.

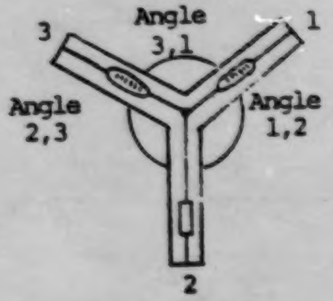

Figure 1

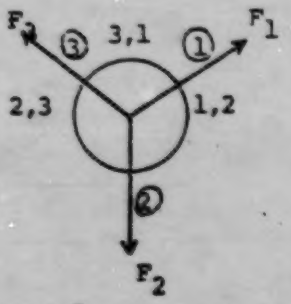

Figure 2

When you lift the CFA off of the paper, you should be able to reconstruct the positions of the arms giving a picture similar to Figure 2. Measure the angles indicated and record these values in the Table. Repeat the procedure using different angles on the back of your sheet of paper. Record those data under Trial 2 in Table I.

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Table I

Trial	Scale Readings	Force in Kilograms	Angles Between Arms
1	arm 1	F_1=	1,2
	arm 2	F_2=	2,3
	arm 3	F_3=	3,1
2	arm 1	F_1=	1,2
	arm 2	F_2=	2,3
	arm 3	F_3=	3,1

The Idea

Inspect the diagram you drew from the Trial 1 data. F_2 is pulling in a different direction than F_3 and F_1. How could you explain how F_1, F_2, and F_3 are related?

Summarize the data you have collected so far and state what you think those data are telling you.

Now return to the discussion area of the laboratory. You, your teacher and your classmates will interpret the data in Table I.

Name____________________

Section__________________

Expansion of the Idea

Part 1: Interpreting Observations

The data in Table I show that one vector is balancing two others. Look at Figure 2.

1. Explain how the ring could be kept in exactly the same place by using F_2 and one other force. Call that force F_4.

2. What would be the magnitude of $\vec{F_4}$?

3. What would be the direction of $\vec{F_4}$?

4. Describe how $\vec{F_3}$, $\vec{F_1}$, and $\vec{F_4}$ are related.

5. How are $\vec{F_2}$ and $\vec{F_4}$ related?

Use the data from one of the trials from Table I. You are going to draw a scale diagram of those data. A scale drawing simply allows a picture to be drawn. In that picture, a specific amount of length represents a specific amount of some other quantity. You might, for example, say that one centimeter will represent 100 gms. If a force was one kilogram, a line 10 cms long would represent that force. Your instructor and the class will decide upon what scale will be used.

Draw a scale diagram of the data you select on a separate piece of paper. Using the two vectors that point in a direction opposite to the third, draw a closed parallelogram. Your figure should look something like the one that follows.

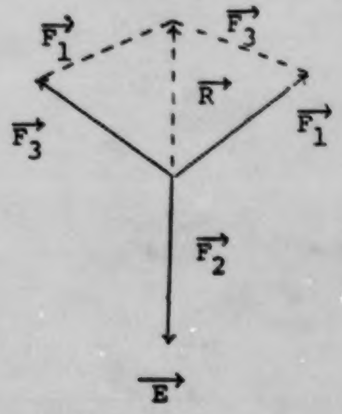

Figure 3

$\vec{R}$ is the resultant of $\vec{F_3}$ and $\vec{F_1}$. Measure $\vec{R}$. What is its value in kilograms? $\vec{R}$ = ______. How do $\vec{R}$ and $\vec{F_2}$ compare?

____

Explain why $\vec{F_2}$ can be called the equilibrant ($\vec{E}$) of $\vec{R}$.

____

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Vectors have magnitude as well as direction. You have just found the magnitude of $\vec{R}$. Now you will find its direction. The compass directions are normally used in giving a vector's direction. Up=north, right=east, left=west, down=south. A vector that makes a 30° angle to the horizontal and points between north and east has a direction 30° north of east or 60° east of north.

What is the direction of $\vec{R}$?

Now write a complete description of $\vec{R}$.

Draw a diagram of $\vec{F}_3$ and $\vec{F}_1$ from the second set of data in Table I. Complete the parallelogram and measure the magnitude of $\vec{R}$.

$\vec{R}$=____________.

Now refer to the data in Table I and compare $\vec{R}$ and $\vec{F}_2$. What did you find?

What is the direction $\vec{R}$?

Write a complete description of $\vec{R}$.

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Name________________________

Section________________________

Expansion of the Idea

Part 2: Problems

Use a scale of 2 cms--100 grams. Draw the following diagrams of vectors that start from the same point. Find the $\vec{R}$ and write a complete description of it.

1. 300 grams 45° N of W and a vector of 500 grams 10° N of E.

$\vec{R}$ = ____

2. Vectors of 400 grams and 600 grams separated by 60°.

$\vec{R}$ = ____

3. 400 grams 10° W of N and a vector of 800 grams 30° E of S.

$\vec{R}$ = ____

Expansion of the Idea

Part 3: Reading Questions

1. Why is scalar a good term to use for the magnitude portion of a vector quantity?

___

___

___

2. You were told that the car was traveling through Jonesville to Smithville. What did that tell you about the velocity of the car?

___

___

___

3. You were told the car had a velocity of 50 mi/hr. What did that tell you about the velocity of the car?

___

___

___

4. Combine your answers to Questions 2 and 3. What kind of quantity is velocity?

___

___

___

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5. You were told that the car started from rest in Jonesville and proceeded to Smithville. The car had a velocity of 55 mi/hr before it stopped. What did that tell you about the motion of the car between the two towns?

6. Examine your answer to Question 5. What kind of quantity is acceleration?

7. You were told that the car went from Smithville to Brownsville at a constant velocity of 55 mi/hr. What change occurred in the car's motion?

8. What happened to the car's motion when at Smithville the car's direction changed toward Brownsville?

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9. An experimental rocket sled achieved a velocity of 284 mi/sec (632 mph) in 5.0 seconds. It slowed to a stop in 1.5 seconds.

   a. Find the average acceleration in reaching maximum velocity.

   b. How far did the sled travel in reaching maximum velocity?

   c. Find the average acceleration while stopping.

INVESTIGATION 2: VECTORS

READING: FORCE

Think about the color yellow. Now try to explain to yourself or someone else what yellow is. You probably immediately think that yellow is a color and that is true. That tells us what it is, but doesn't tell us anything about yellow. Some persons would say that yellow occurs in the color spectrum between orange and green. That also is true and tells us where to find yellow, but we still don't know anything about yellow. Perhaps the only description that can be given of the properties of yellow would come from physicists. Those persons would perhaps give you the wavelengths between which yellow light occurs. That property would not mean much to most persons. Yellow is the type of idea that everyone seems to understand, but hardly anyone can explain.

There is another idea in physics that has the same "everybody-knows-it-but-can't-explain-it" problem. That is force. You just found that force is a vector quantity. It has magnitude and direction. That tells you what force is, but doesn't tell you anything about it. Think about these examples of force.

1. The ball was knocked out of the park by the force of the batter.

2. The force of the rock hitting the window shattered the window.

3. A great deal of force was needed on the oars to row the boat through the water.

4. The two magnets came together with a great deal of force.

5. The moving car hit the tree with so much force the tree was broken off.

6. The force of the wind blew down the building.

Now, substitute for some of the words in the six statements as directed below:

1. In statement one, substitute pushed for knocked.

2. In statement two, substitute pushing for hitting.

3. In statement three, substitute pull for row.

4. In statement four, substitute were pulled for came.

5. In statement five, substitute pushed for hit.

6. In statement six, you decide for what word you should substitute pushed.

Here are some statements with words left out. Some form of the words push or pull can be used in each blank. Be sure to write your answers on a separate sheet of paper.

7. The winning tug-of-war team had enough force to __________ the losing team across the finish line.

8. When the stoppered flask containing water was heated, the steam had enough force to __________ the stopper out.

9. You have to exert a force to __________ on your socks.

10. The moving tennis racket had enough force to __________ the ball across the net.

11. The fisherman had to deliver enough force to the nets to __________ it and its load of fish from the water.

12. The boys gave the car enough force by __________ it that it began to move.

All twelve statements which you have read let you know the most basic property of a force. A force is manifested by a push or a pull.

READING: VECTORS AND MOTION

Throughout this reading you will be asked questions. Record your answers to the questions on your Reading Questions sheet. Answer each question before you continue on with your reading.

Let's review what Investigation 2 told you. Investigation 2 helped you find out about vectors. You found that to be a vector, a quantity has to have magnitude and direction. To say a force is equal to 100 kilograms is not describing a vector. A force of 100 kilograms due east is describing a vector; magnitude (100 kilograms) and direction (due east) are both included. The value of 100 kilograms is the scalar portion of a vector. (1) Why is scalar a good term to use?

The direction of a vector need not use only the conventional direction of north, south, east and west as directions. Imagine a tug-of-war. The winning team has the magnitude of the vector on their side and the winning vector's direction is toward the winning team. The direction of a vector can be given in any terms convenient and understandable by those who hear it. "Toward the yellow house at the corner of the school grounds" is as acceptable a direction for a vector as "35 degrees east of south." The only criterion to use to judge whether or not the direction given for a vector is acceptable is whether or not those persons using that direction will understand it.

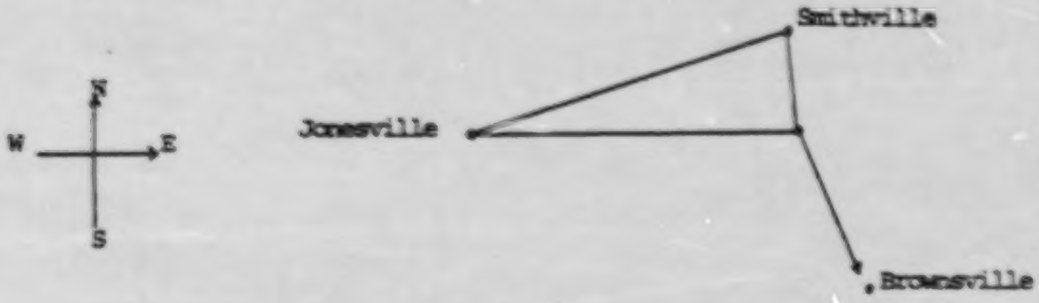

Figure 1

INVESTIGATION 2: VECTORS

Study the diagram in Figure 1. Notice that arrows in the upper left-hand corner (called a compass rose) give the direction in Figure 1. A car travels through Jonesville going to Smithville. You are told that the car has a velocity and travels through Jonesville to Smithville. That is all the information you have. What does that information tell you about the velocity of the car? (2) Next you are told that the car had a velocity of a constant 50 miles per hour between Jonesville and Smithville. (3) What does "50 miles per hour" tell you about velocity?

Combine your answers to the last 2 questions. (4) What type of quantity is velocity?

Now suppose the car stopped in Jonesville and had a measurable velocity when it reached Smithville. What does that information tell you about what happened to the car between Jonesville and Smithville? (Think back to Investigation 1.) You also know that the car moved from Jonesville to Smithville. (5) What does that tell you about the car's motion? (6) What kind of quantity is acceleration ?

The car now goes from Smithville to Brownsville. Its velocity is maintained at a constant 55 miles per hour. (7) What change has occurred in the car's motion? You know a vector has two parts, magnitude and direction. When you change either part you change the vector. The velocity of the car between Smithville and Brownsville was constant. The magnitude portion (or the speed) of the vector did not change. But the direction changed. That is one portion of the vector, so the entire vector has undergone a change. (8) What, then, happened to the car's motion when at Smithville it changed its direction toward Brownsville?

INVESTIGATION 3: FALLING OBJECTS STUDENT GUIDE

Name________________________

Section_______________________

Introduction

How fast does an object fall? In Investigation 1, you learned how to measure the speed of a moving object and how to measure the change in speed with time of a moving object. The object was moving down an incline. In this investigation, you will determine what happens to the motion of an object as it falls.

You will work from photographs of falling balls. Your teacher will have set up a polaroid camera containing high-speed film. Inspect that setup before reading on. A strobe system will also be needed; either a strobe light or a motor-powered stroboscope (slotted disc) will do. If you are using the motor strobe system, you will need a light source. Photograph three kinds of falling balls: 1) a large steel ball; 2) a small steel ball; and, 3) a golf ball. The photographs should give you a series of images of the ball spaced at equal time intervals. Placing a photographic meterstick beside the vertical path along which the ball falls will give you a means of measuring the distance the ball has fallen between successive time periods. You will need to experiment to get the dropping of the ball and the opening of the camera's shutter coordinated.

Exploration

Have someone hold a ball beside the top edge of the meterstick. Someone else needs to trigger the camera shutter. When taking the photograph, the shutter should be opened just before the ball is dropped so that the photograph will show the ball throughout its entire fall. You need an accurate measurement of the number of images per second; around thirty images per second is satisfactory.

Part I

Use the golf ball first and make a photograph of it falling. After coating your photograph with the brush containing the special liquid (provided by Polaroid in the film box), let the photograph dry. Examine the photograph with your group and record your data in Table I.

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1. Examine the photograph you have made of the falling golf ball. Describe the motion of the ball as it falls. Explain why you described the motion as you did.

2. How can you determine the distance the ball has fallen with each successive image?

3. How can you determine the average velocity of the ball with each successive image?

4. How can you determine the acceleration of the ball along the fall?

5. After you have calculated the accelerations and written them in the acceleration column in Table I, make a copy of your data and give it to your teacher.

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Table I

Position of ball on meterstick	Distance between successive images (m)	Average velocity of ball between successive images (meters/second)	Acceleration of ball during fall (meters/second^2)

Average acceleration of the ball ______________ m/sec^2

Part 2

Repeat Part 1 for the two steel balls. From photographs of the falling balls, record the data needed to complete Tables II and III. Again, turn in a copy of the acceleration column of each ball (including the type of ball used) to your teacher as soon as it is available.

Table II

Position of ball on meterstick	Distance between successive images (m)	Average velocity of ball between successive images (meters/second)	Acceleration of ball during fall (meters/second^2)

Average acceleration of the ball__________ m/sec^2

Table III

Position of ball on meterstick	Distance between successive images (m)	Average velocity of ball between successive images (meters/second)	Acceleration of ball during fall (meters/second^2)

Average acceleration of the ball__________ m/sec^2

Write a summary of the data you have gathered so far.

Name____________________

Section__________________

The Idea

1. Examine the data of the average accelerations of the three balls as they fell. How do the values compare?

2. What conclusion can you make about the motion of falling objects?

3. What would you expect the acceleration of a falling baseball to be? Explain your answer.

4. What is the cause of the accelerated motion of a falling object?

5. What name would you give to this kind of acceleration?

6. Why is acceleration due to gravity considered a vector quantity?

7. Describe acceleration due to gravity as a vector quantity.

Name____________________

Section____________________

Expansion of the Idea

Part 1: Problems

1. A stone is dropped from rest from the top of a high cliff.

    a. How far has it fallen after 1.0 second?

    b. What is the stone's speed after 1.0 second?

    c. How far does the stone fall during the second second?

2. A ball is thrown vertically downward from the top of a building at 10.0 m/sec and hits the ground in 10.0 sec.

a. What is the velocity of the ball just before it hits the ground?

b. What is the height of the building?

3. A ball is thrown vertically upward from the top of a building at 10.0 m/sec and hits the ground in 10.0 sec.

    a. What is the velocity of the ball just before it hits the ground?

b. What is the height of the building?

4. A stone is thrown vertically upward at 20.0 m/sec.

a. What distance upward will it have moved when its speed reached 0 m/sec?

b. How much time will have passed when its speed equals 0 m/sec?

c. How much time will be required for the ball to fall the same distance it went up?

d. What will be its velocity when it crosses the point at which it started?

e. How can you explain why Questions 4(b) and 4(c) have the same answer?

5. Bill Fold's hat is stuck on a tree branch. He has a baseball which he would like to pitch upward. The ball would gently nudge the hat to free it and fall back. If he pitches the ball higher than the hat, the hat will go upward with the ball and will perhaps get stuck higher in the tree. He judges the hat to be 4.0 meters above the point where he will release the ball. With what velocity will he have to release the ball?

6. A steel ball is dropped from a height of 30 meters above the earth's surface. The acceleration due to gravity on the earth is 9.8 m/sec/sec. An identical ball is dropped from a height of 30 meters above the surface of the moon. The acceleration due to gravity on the moon is approximately 1.6 m/sec/sec. Which ball will hit the surface it was dropped on with the greatest velocity? Which will reach the surface it is above first?

Name______________________

Section______________________

Expansion of the Idea

Part 2: An Experiment with Trajectory

You will need a Trajectory Apparatus, a piece of graph paper, a piece of carbon paper or paper that shows a mark when touched, and a small steel ball.

An object hurled through space is called a projectile and the path it traces out is called its trajectory. In this activity you are going to use a piece of equipment called a Trajectory Apparatus to make a graphical record of the path a steel ball follows when it is launched from an adjustable aluminum launching ramp in a horizontal direction. Position the launcher so that the ball leaves the ramp horizontally. Place the graph paper on the wooden board and the pre-cut target paper on the target plate. Divide the graph paper along the horizontal axis into at least five equal parts. Move the target plate to the mark closest to the launching ramp. Roll the ball down the ramp and mark on the graph paper where the ball strikes the target plate. Repeat the procedure for at least four more positions of the target plate. Connect the points on your graph paper with a smooth line.

The Trajectory Apparatus:

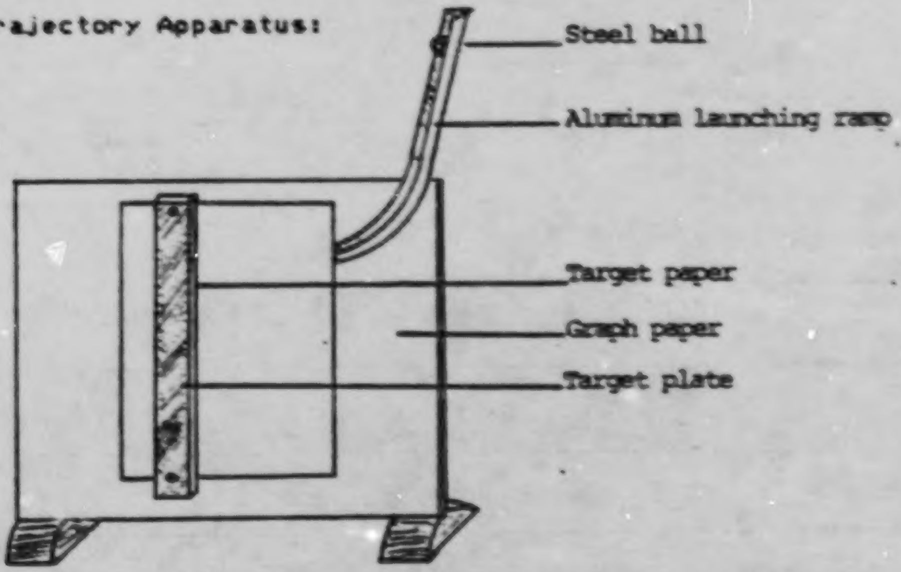

Figure 1

Name________________________

Section________________________

Expansion of the Idea

Part 3: An Experiment with Simultaneous Velocities

Equipment

You will be given an apparatus which has a rod, a compressed spring and a steel ball at each end of the rod. When the compressed spring is released, the two steel balls leave the rod at exactly the same time. Experiment with the apparatus. Do not attempt to collect any data with the apparatus until you are sure you understand how the balls are released at the same time. You will also need two stopwatches. Design a procedure which will allow you to start the stopwatches at exactly the same time. You need to practice with your starting procedure several times.

The collection of data from the apparatus requires at least three persons. One person releases the compressed spring; each of the other two persons observes one of the falling balls and measures the time the ball requires to hit the ground after being released. Observe the falling balls four times and record the measured times in Table IV.

Table IV

	Time (Seconds)	
Trial	Projected Ball	Projected Ball
1		
2		
3		
4		
Average		

1. What do the data in Table IV tell you about the time each ball requires to reach the floor?

2. To answer the following question, consider as well the data you gathered from the Trajectory Apparatus. What kind of path is taken by the ball which landed farther away from the apparatus?

3. What trajectory would the steel ball have as it leaves the launching ramp in the Trajectory Apparatus if there were no gravity?

4. Why is the velocity along the trajectory in Question 3 non-accelerated motion?

Let the equal parts on the horizontal axis of the graph paper from the Trajectory Apparatus experiment represent the distance traveled by the steel ball in equal time intervals. Measure and record in Table V the distance the ball falls during the same time intervals.

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Table V

Time	Distance
1	
2	
3	
4	
5	
6	

5. What do your data tell you about the nature of the vertical motion of the ball after it leaves the ramp?

6. Why is the trajectory of the ball curved?

7. Why are the times of the two balls in Table IV the same?

8. In Question 5, you were to consider that the equal parts on the horizontal axis of the graph paper from the Trajectory Apparatus experiment represented the distance traveled by the steel ball in equal time intervals. Why was this a reasonable assumption to make?

Name_______________

Section_______________

Expansion of the Idea

Part 4: Trajectory Problems

1. An airplane flying on a straight and level path at a speed of 160 Kilometers/hr and at an altitude of 6000 meters drops rations over the middle of an ocean island. The island has a diameter of 1.6 kilometers.

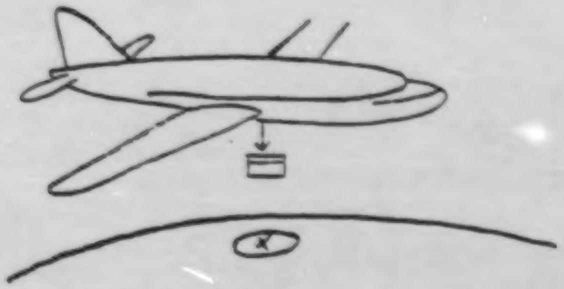

Figure 2

a. If the survivors of a shipwreck are standing exactly in the middle of the island when the package is dropped, how far will they have to go to retrieve the goodies?

b. Where would the airplane have to release the package of rations if the package were to hit right where the survivors are standing?

2. A pistol-firing champion aims at a target 600 feet away from the muzzle end of his gun. The target is 6 feet tall; the bull's eye is three feet above the ground. The shooter holds the gun five feet above the ground so the muzzle of the pistol is exactly parallel to the earth's surface. The bullet leaves the gun with a velocity of 1200 ft/sec. If the bullet hits the target 0.5 second after it leaves the gun, where will it strike the target?

Figure 3

Name_______________________

Section_______________________

Expansion of the Idea

Part 5: Reading Questions

1. In the problem set concerning the trajectory of projected objects (Part 4, Question 1), you had to assume that the rations being dropped from the airplane had an initial velocity of 600 mi/hr. Why was that a reasonable assumption to make?

2. It may not always be reasonable to assume that a projectile will have a constant horizontal motion once the applied force has been removed.

   a. Under what conditions would an object travel through space with a constant velocity?

   b. What factors might affect a missile fired from the earth's surface and traveling through space several miles before striking its target?

3. Optional: If you are interested in working with vectors as applied to projectile motion, determine the firing angle that would allow a cannonball its greatest horizontal distance.

INVESTIGATION 3: FALLING OBJECTS

READING A: ARISTOTELIAN PHYSICS

When men began to think about the motions that occur on the earth, they began to attempt to group and explain them. Some of these ideas began to appear even before the time of Christ. One man's ideas stood the test of argument and time and became the accepted explanations of motion for about 2,000 years. The man was Aristotle and his physics of motion has been known as Aristotelian physics.

Aristotle had explained how and why objects fall. He said that every object has a natural place in the universe. If it is moved from its natural place and released, it will move back. A heavy body is one that would fall to the earth if it were released in air. A light body would rise. The medium, said Aristotle, also affects the body's motion. For example, a block of wood (a heavy object) would fall in air, but if one placed it in water, it would rise to the surface.

Aristotle had also explained acceleration as the body's response to knowing its goal. Since it knows where it is supposed to be, it keeps going faster until it gets there. Acceleration could also be affected by the medium. In a thicker medium, the acceleration is less; in a thinner medium the acceleration is greater since the medium resists the motion of objects within it. He argued that in a vacuum the speed of an object would be infinite, therefore, a vacuum could not exist. To Aristotle, two different objects in the same medium would not have the same acceleration since a heavier one is more able to overcome the resistance of the medium. Therefore, a heavier object will fall faster. In fact, if one object is twice as heavy as the other, its acceleration will be twice as great as the other's. That means if two balls are dropped in air, one with twice the weight of the other, the heavier one will have twice the acceleration.

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READING B: BODIES IN MOTION*

From the time of his discovery of the principle of the pendulum, Galileo had been interested in the study of motion. But until he joined the university faculty, he had neither the time nor the facilities to work on the problem. As he proceeded with his experimentation, he was guided by a precept he had found in the writings of Archimedes. The Greek scientist had warned his successors of the pitfalls of asking too many questions about a problem at once. Before Galileo had paid heed to this warning, men had sought to know why, as well as how, things moved. Galileo chose to ignore the why and concentrate on answering the how. Thus the law of the simple pendulum is merely a scientifically accurate description of an unexplained fact.

Similarly, one of his first experiments on motion was essentially an attempt to show how bodies actually fall. It was also a direct challenge to Aristotelian theory, for the Greek philosopher had written: "A given weight moves (falls) a given distance in a given time; a weight which is as great and more moves the same distance in less time, the times being in inverse proportion to the weights."

According to this reasoning, a forty-pound boulder would fall to earth from atop a sheer cliff two times faster than a boulder weighing but twenty pounds and traveling the same distance. By Galileo's time, some scientists knew this theory was false; however, the writings of Aristotle were still thought irrefutable, and no one dared question their validity. Indeed, a number of experimenters had dropped weights large and small from high walls and church towers, but the results, which disproved Aristotle, were not widely publicized.

Galileo was certain that Aristotle's reasoning was false. He refused to accept the logical-sounding proposition that two stones tied together would fall twice as fast as a single stone. Legend has it that to disprove this belief, Galileo dropped stones from the top of the Leaning Tower of Pisa. Modern historians do not believe he actually used the tower, but he did succeed in proving that a one-pound sphere and a ten-pound sphere would strike the ground almost simultaneously when dropped from a high place.

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*William Bixby, The Universe of Galileo and Newton, (New York: American Heritage, 1964), pp. 27-32.

INVESTIGATION 3: FALLING OBJECTS

Experimenting in public was not for Galileo, but persuasive writing was. Two of his best-known works, Dialogue Concerning the Great World Systems and Discourses on Two New Sciences were written in the vernacular to reach a wide audience. In the latter masterwork, the Discourses, Galileo expressed his theory of falling bodies by means of an imagined conversation between three characters: Simplicio, who believed in Aristotle's physics; Salviati, a spokesman for Galileo, and Sagredo, an intelligent layman who might be persuaded by whichever side was the more convincing. Here is an example of their argument.

Salviati: I greatly doubt that Aristotle ever tested by experiment whether it be true that two stones, one weighing ten times as much as the other, if allowed to fall at the same instant from the height of, say, 100 cubits (a cubit is about 18 inches) would so differ in speed that when the heavier had reached the ground, the other would not have fallen more than 10 cubits.

Sagredo: I, who have the test, can assure you that a cannonball weighing 100 or 200 pounds, or even more, will not reach the ground by as much as a span ahead of a musketball weighing only half a pound.

Simplicio: Your discussion is really admirable; yet I do not find it easy to believe that a bird-shot falls as swiftly as a cannonball.

Salviati: Why not say a grain of sand falls as rapidly as a grindstone? But, Simplicio, I trust you will not follow the example of many others who divert the discussion from its main intent and fasten upon some statement of mine that lacks a hairbreadth of the truth, and, under the hair, hide the fault of another that is as big as a ship's cable. Aristotle says that 'an iron ball of 100 cubits reaches the ground before a one-pound ball has fallen a single cubit.' I say that they arrive at the same time. You find, on making the experiment, that the larger outstrips the smaller by two fingerbreadths...; now you would not hide behind these two fingers the 99 cubits of Aristotle, nor would you mention my small error and at the same time pass over in silence his very large one.

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INVESTIGATION 3: FALLING OBJECTS

Although the words spoken in the Discourses were invented by Galileo, each speaker bore some relation to a real person. Simplicio, spokesman for all the conventional ideas contained in the blind acceptance of Aristotle, may have been modeled after Lodovico delle Colombe, A Florentine scientist and philosopher who had sought to discredit Galileo. Much of what Simplicio says in the Discourses seems to have come from one of Colombe's dissertations.

Salviati, who echoed Galileo, was a reflection of Filippo Salviati, a close friend of the scientist's. Giovan Francesco Sagredo, who became one of Galileo's most respected advisers, was the third interlocutor--the open-minded one in the Discourses.

In proving new theories, Galileo consistently anticipated questions that doubters and dissenters might put to him. His Discourses by its very nature contained both pros and cons. Galileo hoped he had reasoned his arguments carefully enough to convince the Aristotelians, who were the majority, that his ideas were correct.

Galileo believed, for example, that if it were possible to create a vacuum, any two falling objects would travel the same distance in the same time within the vacuum. He felt that in a completely airless space his proposition on free-fall would prove exact, without even a two-finger breadth difference. Actually, even in an ideal situation, there would be some difference, but Galileo would never know this, for he did not know how to produce a vacuum. Aristotle had taught that a vacuum was impossible to create.

* William Bixby, The Universe of Galileo and Newton, (New York: American Heritage, 1964), pp. 27-32.

READING C: GALILEO VS. ARISTOTLE

Everyone knows about Galileo's alleged experiment of dropping unequal weights from the Leaning Tower of Pisa. The experiment proved that Aristotle was mistaken in his belief that heavy objects fall faster than lighter ones.

You can repeat this historic experiment on a small scale by dropping a half dollar and a tiny piece of paper. To eliminate air resistance on the paper, put it on top of the coin as shown. Drop the coin to the floor, giving it a slight spin to keep it horizontal while it falls. The coin and paper will fall together.

"But", you may object, "perhaps currents of air flowing around the falling coin cause the paper to stick to it." To prove this isn't so, hold the coin and paper high in the air. Then, instead of dropping the coin, carry it down at a speed faster than normal falling speed. The piece of paper will be left behind.

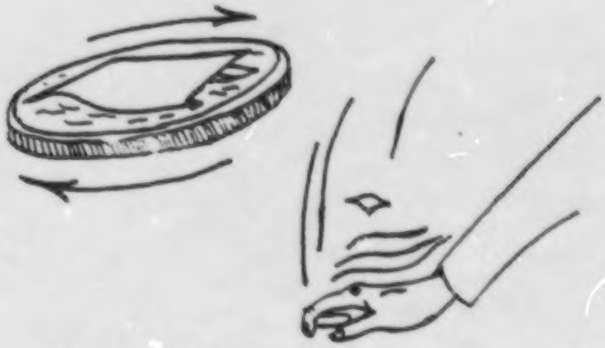

Figure 1

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INVESTIGATION 3: FALLING OBJECTS

READING D: DOUBLE TROUBLE

In this investigation you have studied the phenomenon of projectile motion. Perhaps you found it rather difficult to deal with the fact that an object projected into space has two simultaneous motions--each totally independent of the other. Indeed the idea of constant velocity and constant acceleration being present in the same object at the same time is paradoxical. If it makes you feel any better, you are not alone in your confusion. In fact men of great wisdom denied the simultaneous motions of a projectile for many, many centuries. In the sixteenth century it was reasoned that an object fired from a cannon had two distinct motions. First, the object would have motion resulting from the explosion of the gunpowder, then it would fall to the ground due to its natural motion. In other words, the cannonball would move in the direction it was fired until the gunpowder was gone, then it would fall straight to the earth. The path would look something like this:

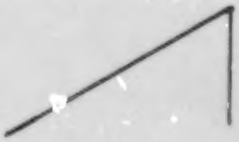

Figure 2

But, Galileo (whom you met earlier in this investigation) proposed quite a different hypothesis. He ascertained that the force of the gunpowder was applied only at the instant of the explosion; the result of that force was the constant velocity of the ball. As soon as the ball left the cannon though, the force of gravity began to cause the ball to accelerate toward the earth at a constant rate.

INVESTIGATION 3: FALLING OBJECTS

He proposed the path of the ball would look like this:

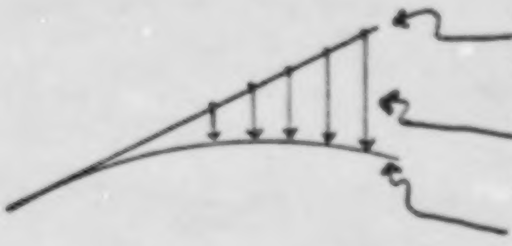
constant velocity of the object due to the applied force
constant acceleration of the object due to the force of gravity
actual path of the ball

Figure 3

The actual path follows a curve called a parabola. Your data from the Trajectory Apparatus gave you concrete evidence that Galileo was correct.

So, now that you are convinced that objects moving through space follow parabolic paths due to the simultaneous presence of constant velocity and constant acceleration, what good is this knowledge? Well, we've already mentioned one important use (although not an altogether pleasant one)--that is the firing of projectiles of war. The ancient catapults and cannons, as well as the modern high-tech artillery and missiles, must be aimed with the ultimate path of the object in mind. You can determine the horizontal distance covered by a fired object and the height it would attain using the knowledge of vectors you gained in Investigation 2. (If you are interested in actually doing this, ask your teacher to help you set up a problem and solve it either trigonometrically or using the parallelogram method.)

Another interesting consequence of the simultaneous motions of bodies in flight had much historical significance. Think. If you drop a coin from the top of a tall ladder, where would it land? Better yet, if you dived from a diving board into a swimming pool situated on a moving ship, would you land in the pool or on the deck of the ship? How silly, you say! The coin would drop at the base of the ladder and you would land in the pool. But, now consider that the earth is moving at all times. So, the free-falling coin leaves your hand while the ladder is in one place and lands on the ground after the ladder has moved a bit due to the motion of the earth. Likewise, you dive from the diving board when the pool is in one position and land after the boat has moved due to its own power as well as the motion of the earth. Well now, are you still sure of your initial response?

INVESTIGATION 3: FALLING OBJECTS

Aristotle and Galileo differed in their ideas concerning this issue as well as the motion of falling bodies. Aristotle used this very issue as evidence that the earth did not move. If the earth had motion of its own, he reasoned, then an object dropped from the mast of a ship would fall into the sea because the ship would move out from under the object. (He never tested this, by the way.) If Aristotle had been right, you would not want to practice your diving on a moving ship.

On the other hand, Galileo argued that an object dropped from the top of a ship's mast would land at the base of the ship because, while the object was falling vertically, it also participated in the horizontal motion of the ship and earth. Thus, a falling object had vertical motion due to the effect of gravity and horizontal motion due to its position in the ship's influence. Today, much experience tells us that Galileo was correct. That means you were right, too. So the next time you are diving and swimming on board a ship, relax! Your vertical acceleration toward the pool accompanied by your simultaneous horizontal motion within the ship's influence will guarantee you will land in the pool. Refreshing, isn't it?

NOTES

INVESTIGATION 4: FORCE AND ACCELERATION STUDENT GUIDE

Name________________________

Section______________________

Introduction

An automobile accelerates through an intersection after stopping at a stop sign only to accelerate negatively again to stop at the next stop sign. An apple, being released from a tree, accelerates until it hits the ground. A baseball accelerates from rest at the back of the pitcher's throw until it has a velocity of about 90 miles an hour toward the batter. How are these events related. What causes the accelerations described? What variables are involved in producing the acceleration of an object? How are these variables related? These questions make up the goal of the next four investigations.

The purpose of this investigation is to determine how the acceleration of a cart changes when a constant force acts on the cart. You should also find out what effect changing the distance makes on the acceleration you measure.

Your teacher will explain the apparatus you will use. To get your apparatus ready to use, attach the spring to the zero meter end of the meterstick. Hook the spring scale onto the other end of the spring as shown in the drawing below.

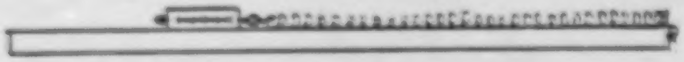

Figure 1

You will need to determine the distance the spring has to stretch to give you a force of 200 grams. You may want to put masking tape on your meterstick to mark the stretch that will provide the force you will need.

Exploration

Put your cart on the balance and add weights until your cart and the weights together weigh two kilograms. Take the cart off the balance and add one kilogram weights until the total weight of the cart is six kilograms. Attach the free end of the spring (the other end should still be attached to the meterstick) to the front of the cart and find a way to consistently make 200 grams of force accelerate the cart. Practice accelerating the cart with a constant force of 200 grams for a distance of one meter. That force is not balanced by anything and is, therefore, called an unbalanced force.

1. To determine the acceleration of the six kilogram cart over a distance of 0.50 meter, make at least three measurements of the time it takes for the cart to start from rest ($v_i=0$) and travel the 0.50 meters; average those measurements. Record your data in Table I. How can you keep the force constant throughout the trip?

2. Repeat the foregoing procedure, but this time determine the time the cart takes to travel a distance of 1.0 meter. Record your data in Table I.

3. Change the distance to 1.50 meters and repeat the procedure again. Record your data in Table I.

Table I

Distance (m)	Time (sec)	Acceleration (m/sec^2)	Average Acceleration
0.5			
1.0			
1.5			

Write a general summary of the data you have collected.

The Idea

1. Use one of the equations from Investigation 1 to find the acceleration of the cart in every trial. Which equation will you use?

2. Determine the average acceleration for each distance. How do the average accelerations compare?

3. If someone were convinced that the acceleration was constant, how would you respond?

4. What effect does changing the distance have on the acceleration when the force is kept the same?

5. What results when a constant force is applied to an object?

Name____________________

Section____________________

Expansion of the Idea

Part 1: Questions and Problems

1. How can you determine by watching a body whether or not an unbalanced force is acting on it?

2. Joe Blow made a toy rocket-powered car. He wanted to measure the average acceleration of the car. To do that, he timed the car over a distance of 0.5 m. He found that the car, starting from rest, passed the 0.5 m mark so rapidly that he could not accurately measure the time. His friend, Jack, suggested that he increase the distance until the time became measurable. Joe said that changing the distance would change the measurement of the acceleration even though the car was still moving under full power. If you were there, how would you respond to the argument?

3. Using his rocket-powered car, Joe took the following data:

Time	0.9 sec
Distance (1)	2.0 m
Distance (2)	4.0 m

a. Determine the car's acceleration.

b. Assuming the acceleration of the car does not change, find the time required for the car to go 4.0 meters starting from rest.

c. Assuming the acceleration and weight of the car do not change, how does the force acting on the car change as time and distance increase?

Name____________________________

Section____________________________

Expansion of the Idea

Part 2: An Experiment with Variable Forces and Acceleration

Everyone knows that the acceleration of a cart will increase if the force acting on the cart increases, providing all other factors remain the same. The goal of this experiment is to determine how much the acceleration changes when the force acting on the cart is changed by a definite amount. For example, we determined the acceleration of a 6 kg cart when a 200 g horizontal force was acting on it. How will the acceleration change if we double the horizontal force acting on the cart? Your teacher will explain the apparatus you need.

As you did in the Exploration, mark the meterstick with masking tape. Mark it to know the length the spring has to stretch to provide accelerating forces of 100 g, 200 g, 300 g, 400 g, 500 g, and 600 g.

On a table top or other level surface, measure and mark a distance of 1.0 meter (masking tape pieces provide convenient, temporary markings). The weight of the cart should be the same as in the Exploration.

1. Using a horizontal force of 100 gms, make three measurements of the time required to accelerate the cart from rest through the distance of 1.0 m. Record the distance and times in Table II.

2. Gather data concerning the time and distance when the horizontal force is 100 g, then 200 g, 300 g, 400 g, 500 g, and 600 g. Record all data in Table II. If the time measurement becomes less than 1.0 seconds, increase the distance to 1.5 meters and continue.

Table II

Force (g)	Distance (m)	Time (sec)	Average Acceleration (m/sec^2)
100			
200			
300			
400			
500			
600			

Write a general summary of the data in Table II.

Your teacher will work with you to combine data from all laboratory groups in your class in order to make a class graph. Graph acceleration on the vertical axis and force on the horizontal axis. Be sure to make a smooth line that shows how the points you plotted are arranged.

1. Where should the point 0 gm, 0 m/sec^2 be on the graph?

2. What does your graph show about the change in acceleration when the force changes?

3. Choose two points on your graph such that one point represents twice the force of the other point. What change in acceleration is found?

Name____________________

Section____________________

Expansion of the Idea

Part 3: An Acceleration Problem

1. On naval carriers, when fighter planes land, a cable catches the plane and decelerates it. On one occasion a plane came in at 100 m/sec and was stopped in 100 m.

    a. Find the average acceleration of the plane.

    b. On the next occasion, the same plane came in at the same speed and was stopped in 75 m. Find the average acceleration of the plane.

    c. Compare the forces acting on the plane on the two occasions. (You will not be able to give exact magnitudes for the forces, but you should be able to compare them in mathematical terms.)

Expansion of the Idea

Part 4: Reading Question

Use your knowledge of force and acceleration and the data given in the reading to design a velocity versus time graph for the cart if 80 grams of force were constantly applied to the cart.

INVESTIGATION 4: FORCES AND ACCELERATIONS

READING: FORCES AND ACCELERATIONS

In Investigation 4, you found a relationship between acceleration and force. That relationship can be expressed as a is proportional to F. It can also be written F=ka. As you will see in this reading, there are many common applications of this relationship.

When you are riding a bicycle and you want to speed up (accelerate), you simply push harder on the pedals. The harder you push, the greater the acceleration given to yourself and the bicycle. If you want greater acceleration, you stand on the pedals, thereby pumping the bicycle. In doing so, you are increasing the force so that the acceleration will be greater. If you ride your bicycle regularly for several months, you will find that your legs grow stronger and you can apply even more force to the pedals and thereby achieve even greater acceleration.

Your car works somewhat like your bicycle. The engine is the source of the force which is delivered to the rear tires. The accelerator pedal governs the amount of force the engine will apply to the tires. You can therefore control the acceleration of the car. If you want greater acceleration, you push the accelerator pedal down farther. If you want the acceleration to be less (from rest), you do not push down as far. If you want maximum acceleration, you push the pedal down as far as it will go.

There are other factors involved in the motion of a car which we are not ready to go into yet. For example, why is it that after the car is moving you still have to hold the pedal down somewhat just to maintain a nearly constant speed. Also, why is it that with some cars when you push the accelerator completely to the floor, the tires spin (squeal) and you leave rubber on the road? We will discuss these kinds of questions after we have invented more concepts of motion.

The relationship between the force applied to an object and its consequential acceleration was known intuitively long before Sir Isaac Newton expressed it verbally. For example, several centuries before Christ, catapults were being built as weapons of war to throw spears and rocks farther than a man could shoot an arrow or throw a spear. It had been known that the farther back a bow was pulled, the farther the jettisoned arrow would fly. When catapults were built, some of the fancier ones had notches built into them which would allow the catapultist a range of forces which he might apply to the projectile. Obviously, it was known that the projectile would go farther when the firing arm was cranked back more notches. Today, we say that when the force of the catapult on the projectile was exerted for a greater period of time, the projectile would achieve a greater acceleration, thus, have greater velocity when it left the launcher. The greater the initial velocity a projectile has, the greater the distance it will travel.

The statement F=ka actually says more than just the acceleration increases when the force increases. It tells how much the acceleration will increase when the force is increased by a known amount. For example, if the force is doubled, F=ka tells us that the acceleration will also double, assuming no other changes (than force) are made in the equipment being used.

The pictures below show a cart system somewhat like the cart system you used in Investigation 4. Instead of moving on bearing wheels, this cart glides on a layer of air. The layer of air is produced by an air trough which is a tube with many holes in the trough surface. A vacuum cleaner-like device can be connected to the air trough in reverse so that it blows air instead of drawing it in. The air being forced through the holes provides the air cushion for the cart (or glider). The glider can then be connected by string or ribbon to a weight which hangs over a pulley at the edge of a table. The weight and pulley system can move as freely as possible in response to the force of gravity on the weight. The air trough is leveled so that gravity does not affect the motion of the glider directly.

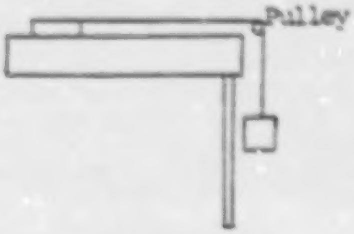

Figure 1

An arrangement is made to photograph the glider as it moves along the air-trough. The photographic system is similar to that which you used in Investigation 3. Repeated pictures of the glider are made through stroboscopically controlled time intervals. The positions of the glider are shown by an arrow moving along a meterstick. The divisions are in units of centimeters.

Two photographs of the glider moving across the air troughs are shown below. In photograph A, the pictures of the cart are made every 0.40 seconds. The cart was already moving when the first picture was made in each photograph.

INVESTIGATION 4: FORCES AND ACCELERATIONS

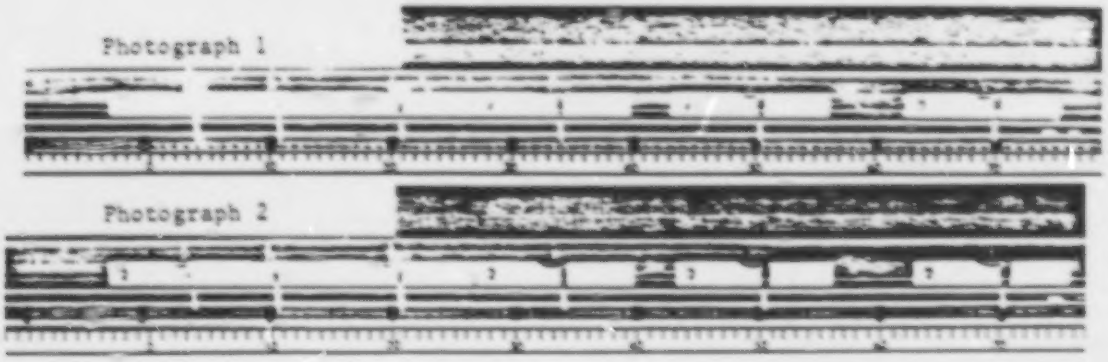

Figure 2

In photograph B, the pictures of the cart were made every 0.20 seconds. The weight hanging from the pulley in Photograph A was 20 g. In photograph B, the hanging weight was 40 g.

The following tables show data which has been taken from each photograph.

Table 1 (Photograph A)

Time (sec)	Position (cm)	Distance Traveled (cm)	Velocity (cm/sec)
0	3.9		
0.4	10.6	6.7	16.75
0.8	20.8	10.2	25.5
1.2	34.0	13.2	33.0
1.6	50.3	16.3	40.75
2.0	70.2	19.9	49.75

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Table II (Photograph B)

Time (sec) Velocity (cm/sec)	Position (cm)	Distance Traveled (cm)
0	8.2	
0.2 28.0	13.8	5.6
0.4 35.0	20.8	7.0
0.6 41.5	29.1	8.3
0.8 51.0	39.3	10.2
1.0 59.5	51.2	11.9
1.2 69.0	65.0	13.8
1.4 78.0	80.6	15.6

The graphs below show data from the two tables above. The graph at the left shows the pattern of points when the velocity (in cm/sec) of the cart in Photograph A is plotted against the time (in sec). The same variables are plotted in the graph at the right for Photograph B.

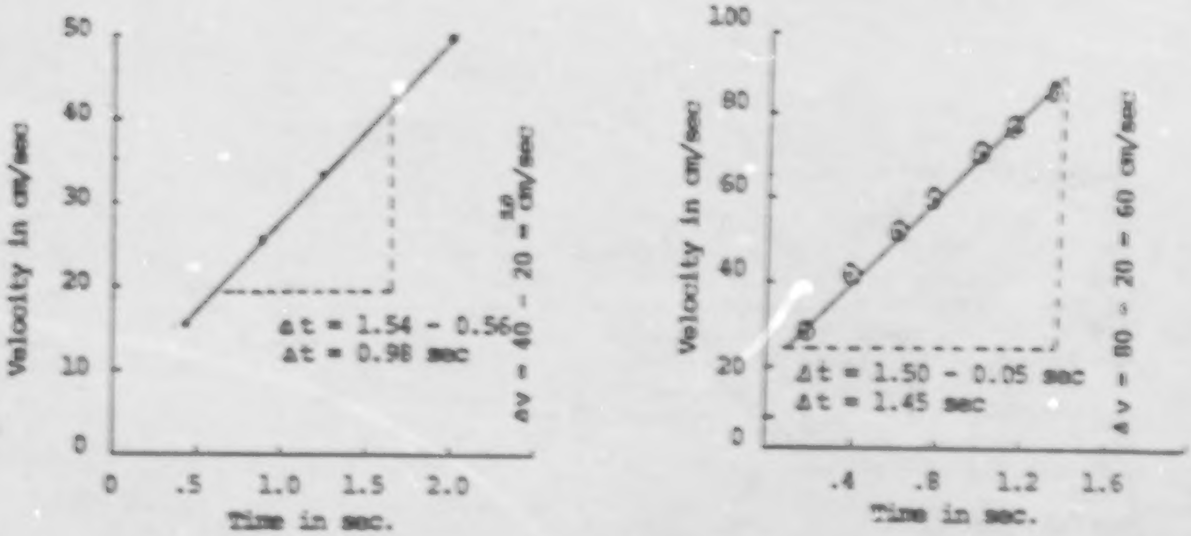

Figure 3

Notice that information is also provided on the graphs from which we can find the slopes of the lines. The slope of a line is given by $\triangle y/\triangle x$ which on these graphs is $\triangle v/\triangle t$. Recall from earlier investigations that $\triangle v/\triangle t$ has been given the name acceleration. Therefore, the acceleration of the cart in Photograph A is:

$\triangle v/\triangle t$=20 cm/sec/0.98 sec=20.4 cm/sec/sec.

The acceleration of the same cart in Photograph B is:

60 cm/sec/1.45 sec=41.4 cm/sec/sec.

That means the acceleration of the cart in Photograph B is almost exactly twice that of the cart in Photograph A.

The forces producing the accelerations are also different. In Photograph B, the hanging weight is double that in Photograph A. Therefore, we can see in this situation that if 1F produces an acceleration of 1a, then 2F produces an acceleration of 2a. The results of this situation support the general statement F=ka. We would therefore expect 3F to produce an acceleration of 3a.

INVESTIGATION 5: A PROPERTY OF MATTER STUDENT GUIDE

Name________________________

Section______________________

Introduction

When you step on a bathroom scale, you measure your weight. Most purchases we make such as meat, vegetables, and sometimes ice cream cones are made in terms of weight. Bridges specify the maximum weight they can support. Trucks are rated according to hauling weight limits. When a truck smashes into a building or through a wall or fence, what property of the truck causes the damage? (Remember, speed is not a property of an object.) In this investigation, we will identify another property of matter which is sometimes confused with weight.

Exploration

Clamp the inertial balance to the table with the C clamp as shown in Figure 1 below. Set the balance in oscillation by pulling it horizontally 10 cm to the side.

Count the number of complete oscillations (a swing from the starting position, through the resting position, and back to the starting position) occurring in fifteen seconds. (You may need to let the balance strike a piece of paper in order to count the number of swings.) Repeat the exercise twice more. Record your data in Table I.

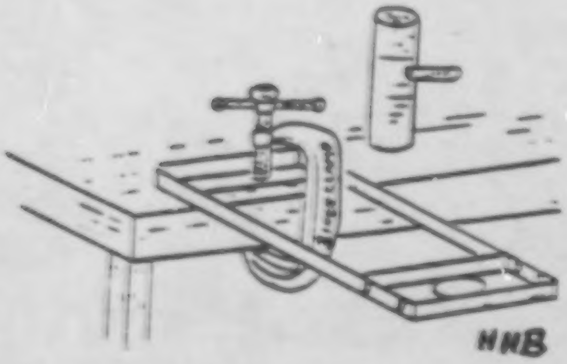

Figure 1

Next, load the balance with the metal cylinder provided. Repeat the measurements you made in the previous section. Take three readings. Record your data in Table I. Load the balance with a 500 g weight. Repeat the measurements you made in the previous section. Take three readings. Record your data in Table I.

Table I

	Number of Oscillations in 15 Seconds		
Trial	Unloaded Balance	Loaded Balance (Cylinder)	Loaded Balance (500 g)
1			
2			
3			
Average			

The Idea

1. From Investigation 3, what is the direction of the acceleration vector of a falling object?

____

2. From Investigation 4, what is needed to cause the acceleration of an object?

____

____

3. What force causes the acceleration of a falling body?

____

4. The term that is used for the force due to gravity on any object is weight. What is the force due to gravity on you?

____

5. In this investigation, how did the number of oscillations made in fifteen seconds by the unloaded and loaded balances compare?

6. What explanation can you give for these data?

7. What effect does gravity have on the motion of the inertial balance? Explain your answer.

8. What effect does weight have on the motion of the inertial balance? Explain your answer.

9. What factor(s) did influence the motion of the inertial balance?

Name____________________________

Section__________________________

Expansion of the Idea

Part 1: An Experiment with Kilograms and Newtons

Now that we have found that weight and mass are different properties of an object, we need to use different units when we talk about them. You now know that weight is a force. In the metric unit system, force is measured in newtons (abbreviated N). So we can use the newton as a unit of weight. Mass is measured in grams or kilograms. You will now investigate the mathematical relationship between kilograms and newtons.

Hang 500 grams on the gram spring scale and record the reading in kilograms in Table II. Repeat this measurement twice. Using the newton scale, repeat the measurements you made in the previous section. Again record your data in Table II. Next, hang 1000 grams on the gram scale and record the measurements in Table III. Repeat the procedure using the newton scale.

Table II

Grams	Kilograms	Average	Newtons	Average
500 g	1		1	
	2		2	
	3		3	
	Total			
1000 g	1		1	
	2		2	
	3		3	
	Total			

1. From your data, what constant would allow you to equate kilograms and newtons?

2. What does the value you obtained in Question 1 represent? (Think back to Investigation 3.)

3. What equation for weight could you derive from your data?

Name____________________

Section____________________

Expansion of the Idea

Part 2: Questions and Problems

1. What is your mass (in kg) on earth?

2. What is your weight (in newtons) on earth? __________

3. If the force due to gravity on the moon is approximately 1/6 that on the earth, what would be your mass (in kg) on the moon? Explain your answer.

4. What would be your weight in newtons on the moon?

5. You take a 400 gram weight from your laboratory on earth and send it space mail to the moon. Your friend on the moon hangs the weight on a spring scale that measures grams (just like the one you used in class). What reading will your friend make from the scale? Explain your answer.

6. What problems, if any, would be encountered if you were to go bowling on the moon? Explain any answer you give.

Name____________________

Section____________________

Expansion of the Idea

Part 3: Reading Questions

1. What is an unbalanced force? What does an unbalanced force do to an object?

2. Suppose you were in a weightless environment. If you looked in a mirror, would you appear any thinner? Explain your answer.

3. Under what condition did Einstein say the mass of an object would increase?

4. Explain a situation in which knowing the mass of an object would be preferable to knowing its weight.

INVESTIGATION 5: A PROPERTY OF MATTER

READING: MASS--NOT A WEIGHTY MATTER

You have been investigating the idea of mass. You know that the greater the mass an object has the greater its tendency to resist motion. Close your eyes. Imagine that you push two objects of greatly differing mass--say, a large boulder and a small pebble. Because the boulder has a very large mass and, therefore, will resist a change in its motion more, your push will have little affect on it. On the other hand, the pebble will easily be moved by your push. The tendency an object has to resist a change in its motion is called inertia. Inertia has no units, but is directly proportional to (as well as due to) the mass an object has.

Now suppose the boulder and the pebble are coming toward you at 55 miles/hour. Which one would be easier to stop? Since the boulder has greater mass and, therefore, greater inertia, one will have to exert a much greater force to stop it.

When a cup sits on a table, we have a pair or couplet of forces in balance. Consider the forces acting on the cup. The force due to gravity pulls downward on the cup with a magnitude of ma , but the table counterbalances this force with an equal and upward force. We may conclude from this and similar examples that only unbalanced forces move and accelerate objects.

The mass of an object depends on the quantity of matter in the object, or in other words, on the number and kind of molecules which make up the object. The difference between weight and mass is most transparent when we examine an object in space. If we travel a distance above the earth's surface equal to the radius of the earth, the object will weigh only one quarter of what it weighed on earth. In other words, if you weighed 100 pounds on earth, you would only weigh 25 pounds at an altitude of 4000 miles or 2500 Kilometers above the earth. (4000 miles is the approximate radius of the earth.) What a marvelous way to lose weight, you say, clearly superior to all the diets you have tried! But what does it mean to lose weight in space? Does it imply that you will lose both your arms and both your legs? Weight is the force due to the earth's gravity which acts on you. It changes as we increase or decrease distance from the center of the earth's gravitational field which is the geographical center of the earth. But you don't add or lose any matter. This means that your weight changes, but your mass remains the same. When would you become weightless?

INVESTIGATION 5: A PROPERTY OF MATTER

How do we know that your weight in the previous paragraph would be only one quarter of what it was on the earth's surface? This calculation comes from the Law of Universal Gravitation formulated by Sir Isaac Newton which will be studied in the future in this course. At this point, let us consider only two aspects of this law. That the force due to gravity becomes weaker as we go farther away from the earth's surface seems obvious, but Newton also stated a relationship which you may find paradoxical: not only does the earth's gravitation produce a force which attracts you, but you also exert a force of equal magnitude on the earth!

For hundreds of years after Newton, scientists believed that while weight varied with location in a gravitational field, mass remained constant regardless of location. Are there situations under which mass does change? Although such a study is part of an advanced topic called Modern Physics, we will mention a few ideas at this time to stimulate your thinking. Einstein suggested that mass was related to energy by the famous equation $E=mc^2$, where c is the velocity of light. Although we have not studied this topic in enough depth to know why, this equation predicts that as an object nears the speed of light, its mass will increase. Mass, then, remains constant and unchanging, except when it travels at speeds near the velocity of light. Of course, this can happen only in man-made accelerators, since the speed needed is 186,000 miles/sec or 3.0×10^8 m/sec.

Name________________________

Section______________________

Introduction

How will the acceleration of the cart change if you increase the cart's mass, but keep constant the horizontal force acting on the cart? This question suggests the goal of this experiment which is to find the relationship between the mass of the cart and the acceleration when a horizontal, unbalanced force acting upon it is not changing. That relationship needs to be stated mathematically.

Exploration

Again arrange to measure the time required for the cart to accelerate constantly from rest over a distance of 1 meter. That distance is held constant throughout the investigation. You will use a horizontal, unbalanced force of 2 N throughout this investigation. Start with a cart mass of 6 kg. Take three measurements of the time required to constantly accelerate the cart with a force of 2 N over the distance of 1 meter. Record your data in Table I. Then change the cart's mass to 5 kg and again measure time and distance. Continue decreasing the mass by 1 kg and recording times and distances until data for a 2 kg cart have been collected. Remember the distance the cart travels is a constant 1 meter.

Table I

Mass of Cart (kg)	Time (sec)	Acceleration (m/sec^2)	Average Acceleration (m/sec^2)
6.0			
6.0			
6.0			
5.0			
5.0			
5.0			
4.0			
4.0			
4.0			
3.0			
3.0			
3.0			
2.0			
2.0			
2.0			

Share your data with your fellow students. Your teacher will prepare a table like Table II on the chalkboard or on a plastic sheet for the overhead projector. Write the average accelerations you calculated in the space opposite the appropriate cart mass.

Use the acceleration each group found for each mass and calculate the average acceleration for each mass.

TABLE II

Mass of cart(kg)	Average Accelerations Each Laboratory Group 1	2	3	4	5	6	7	8	Average Acceleration each mass
6									
5									
4									
3									
2									

Make a graph of your data (Table I) or the combined class data (Table II), graphing acceleration on the vertical axis and mass of the cart on the horizontal axis. Draw a smooth curve on your graph which, as accurately as possible, represents the points plotted. Call this Graph A. Next, draw a graph of acceleration against 1/mass of the cart. Plot acceleration on the vertical axis and 1/mass on the horizontal axis. Again draw a smooth curve on the graph. Call this Graph B.

To summarize the data collected, describe the curves on Graphs A and B.

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Name________________________

Section________________________

The Idea

1. Which graph is more useful in helping you determine a relationship between a and m?

2. What does the more useful graph show about how the acceleration changes when the mass changes?

3. Write the mathematical relationship here.

INVESTIGATION 6: MASS AND ACCELERATION STUDENT GUIDE

Name____________________

Section____________________

Expansion of the Idea

Part 1: Questions and Problems

You now have an equation that describes the relationship between mass and acceleration.

1. Using your graph, find the value of the constant k. What are its units?

2. If 200 g of force were applied to a car that has a mass of 1000 kg, what acceleration would it have? (Assume no friction affects the car's motion.)

3. If 200 N of force were applied to a flea with a mass of 1×10^{-6} kg, what acceleration would it have?

INVESTIGATION 6: MASS AND ACCELERATION

READING: MASS AND ACCELERATION

Suppose you applied the same force to two different objects: for instance, a baseball and an elephant. On the basis of what you have already found out about force, mass, and acceleration, you would probably agree that the baseball would be given the greater acceleration. The baseball has a much smaller mass than the elephant and, therefore, given an equal force, will accelerate at a much greater rate.

One might also reason that in order to bring the elephant and the baseball to the same rate of acceleration, a much larger force must be exerted on the elephant than on the baseball. Let's assume that the elephant is a small elephant with a mass of about 250 kg and that the baseball has a mass of 0.3 kg. How much greater force do you think must be applied to the elephant to accelerate it and the baseball at a rate of 10 m/sec/sec? You don't have enough data at this time to make an absolutely correct response, but you can make an educated guess. The elephant's mass is about 833 times that of the baseball, so, it might be reasonable to assume that the force on the elephant would need to be about 833 times greater than the force on the baseball. That's a lot of force! But, then think of the bat one would have to use to hit an elephant-size home run!

In Investigation 7, we will put the data concerning force, mass, and acceleration together. Then you will be able to determine the exact force required to accelerate a 250 kg elephant at a rate of 10 m/sec/sec--just in case you ever need to know such a thing!

INVESTIGATION 7: THE LAWS OF MOTION

STUDENT GUIDE

Name____________________

Section____________________

Introduction

In Investigations 4, 5, and 6, you gathered data that enabled you to write statements describing the relationships between acceleration and force, and acceleration and mass. You have also gained some understanding of the difference between mass and weight.

Exploration

The data for this investigation will be the ideas invented in Investigations 4, 5, and 6.

1. State the relationship between force and acceleration you found in Investigation 4.

2. State the relationship between mass and acceleration you found in Investigation 6.

3. State the principal idea from Investigation 5.

4. The statements made in Questions 1 and 2 can be stated in the form of mathematical equations. Write those equations and solve each for acceleration.

(1) a =____

(2) a =____

The Idea

Combine the two statements made in Question 4 above into one statement. Write that statement here.

____

This relationship is known as Newton's Second Law of Motion. Restate the mathematical equation in your own words.

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Name________________________

Section________________________

Expansion of the Idea

Part 1: An Experiment--The Old Table Cloth Trick

Place a piece of paper on the laboratory table. The teacher will have a collection of several objects. Select one object, place it on the piece of paper, and trace the outline of the object with a pencil. Remove the object. Place a second piece of paper on top of the first. Situate the object on the paper so it sits within the outline you drew on the bottom piece of paper.

1. Describe what happens to the object when the top paper is quickly pulled from under the object.

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2. Describe what happens to the object when the top paper is slowly pulled from under the object.

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3. What explanation would you give for your answers in Questions 1 and 2?

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4. Read Mass vs Weight. Why is it that a slow continuous increase in the downward force breaks the string above the massive ball, but a sudden increase breaks the lower string?

5. What name could be given to the property of an object responsible for the results obtained in the table cloth exercise and the hanging ball incident?

6. Earlier in the course, you made several equations that describe the motion of objects. Some of those equations follow.

   a. $v_f = v_i + at$

   b. $d = v_i t + 1/2\ at^2$

   c. $v_f^2 = v_i^2 + 2ad$

We know that if an unbalanced force acts on an object, that object will have an acceleration. What value will the acceleration have if all the forces acting on the object are completely balanced, and thus the net force acting on the object is equal to 0 newtons?

7. Show how the above three equations should be rewritten when an object in motion has an acceleration of 0.

a. ______________________________

b. ______________________________

c. ______________________________

8. Looking at the three equations you just wrote, what will the motion of an object be like if no unbalanced force is acting on it?

____

____

9. The data you collected from The Old Table Cloth Trick, the reading Mass vs Weight, and the preceding questions can be used to develop a statement of Newton's First Law of Motion--sometimes called the Law of Inertia. Write that law here.

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Name____________________

Section____________________

Expansion of the Idea

Part 2: A Think Experiment

1. Suppose you were hammering a nail into a piece of wood. Describe what would happen to the nail. Describe what would happen to the hammer.

2. Suppose you blew up a balloon. If you released the balloon before you tied it off, what would happen to the balloon? In what direction would the air from the balloon move?

3. Suppose you were duck hunting in a small boat on the lake. You fire your gun while the muzzle is horizontal to the water. What direction would the boat move?

4. What phenomenon do Questions 1, 2, and 3, have in common? Mention forces in your discussion.

5. These data can be explained by Newton's Third Law of Motion--sometimes called the Law of Action and Reaction. Write that law here.

Name____________________

Section____________________

Expansion of the Idea

Part 3: Summarizing

Summarize the three laws you have worked with in the preceding sections of the investigation. Give each law a name that will adequately describe its meaning.

1. ____
____
____

2. ____
____
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3. ____
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Name________________________

Section________________________

Expansion of the Idea

Part 4: An Experiment with Exploding Carts

Using a piece of masking tape, mark a line about 25 cm long across your laboratory table. Determine the mass of the two spring-loaded carts and record the measurements in Table I. You may need to add balance weights to one (or both) of the carts to make their masses equal. (Push the cylinders into the carts, if someone has not already done so.) Label one cart Cart A and the other Cart B. Position the carts such that one cart is on each side of the line and the front faces of the carts touch each other. (Consider the front face to be the end that has the spring-loaded cylinder protruding from it.)

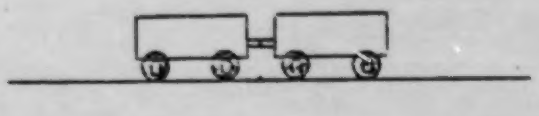

Figure 1

You are now ready to make your measurements. Two group members should have stopwatches; one person should time Cart A and the other person Cart B. One group member should release the spring on one of the carts. Measure the time necessary for each of the carts to come to rest and the distance each travels from the line. Practice the exercise until the two persons with stopwatches can synchronize their starting times. When you are ready to begin, repeat the measurements three times. Record your data in Table I.

TABLE I

		mass	distance	time	$\triangle v$
Cart A	1				
	2				
	3				
Average					
Cart B	1				
	2				
	3				
Average					

Next, double the mass of cart B by adding weights to it. Call this cart C. Repeat the measurements you made in the previous section. Record your data in Table II.

TABLE II

		mass	distance	time	$\triangle v$
Cart A	1				
	2				
	3				
Average					
Cart C	1				
	2				
	3				
Average					

1. How did the change in velocities of carts A and B compare?

   ____

2. How did the change in velocities of carts A and C compare?

   ____

3. What explanation would you give for any differences in your answers to Questions 1 and 2?

   ____

   ____

   ____

4. Examine your data in Tables I and II. What mathematical equality could you write to explain the data you obtained from your work with carts A and B and carts A and C?

   ____

   ____

   ____

5. What name would you give the product of mass and change in velocity?

   ____

6. In your previous work in science you may have encountered the laws of conservation of mass and energy. There is also a Law of Conservation of Momentum. State that law. How was momentum conserved in your investigation of the Exploding Carts?

7. Rewrite Newton's Second Law of Motion (F=ma) in terms of the variables F, v, m, and t.

8. How can you apply this new equation to the data you obtained from The Old Table Cloth Trick and the experiment with the hanging ball in the reading Mass vs Weight?

Name______________________

Section____________________

Expansion of the Idea

Part 5: Problems

1. Explain, using Newton's Laws, why you push some objects aside with your foot instead of kicking them out of the way.

2. Two balls are lifted several feet off the ground and dropped. One has a mass of 0.5 kg and the other has a mass of 2 kg.

   a. Find the gravitational forces acting on them.

   b. How do the gravitation forces acting on them compare?

3. Would an object in space (at 0 G gravitation) still have inertia? Explain your answer.

4. A force of 6 newtons acts on a mass of 12 kg for one second and then on a mass of 24 kg for one second. Assume that the masses were initially at rest and no other forces are acting.

   a. Find the acceleration of each mass.

   b. How do their final velocities compare?

5. Two ice pucks of different mass (one is a 3 Kg puck and the other is a 5 Kg puck) are accelerated from rest to velocities of 10 m/sec in two seconds.

   a. Find the accelerations on each puck.

   b. Compare the forces acting on the pucks.

6. A man on a lake in a large motor boat pulls a light canoe up to him with a rope.

   a. Which boat is being moved? Explain.

   b. Compare the forces acting on the two boats.

   c. What does Newton's Second Law tell you about the motions of the two boats?

7. Golfers wish to maintain contact with the golf ball for as long as possible to achieve the greatest distance possible. Karate experts, on the other hand, want to apply the quickest contact possible in order to break a board with their hands. Discuss these paradoxical situations in light of the equation $F=m\triangle v/t$.

8. A boy with a mass of 75 Kg, running with a velocity of 3.0 m/sec, jumps onto a sled that has a mass of 10 Kg. If the sled had a velocity of 2.0 m/sec, and was already moving in the same direction as the boy, what would be the velocity of the boy and the sled together? (Assume the sled is moving on level snow).

Name______________________

Section____________________

Expansion of the Idea

Part 6: Reading Questions

1. In the last paragraph of the reading, Laws of Motion, the author stated that "... the first (law) describes the motion of a body in equilibrium. What do you think the author meant by that statement?

2. If there is little or no air in space, what does a rocket push against in order to propel itself through space?

READING A: ISAAC NEWTON*

NEWTON (1642-1727). Isaac Newton was born prematurely on Christmas Day, 1642, at the Manor House of Woolsthorpe, near Grantham, in Lincolnshire, England. He was the posthumous son of a yeoman farmer who was Lord of the Manor of Woolsthorpe. Newton was so small at birth that his mother said she could have put him in a quart pot; so lacking in vitality, that the two women who went to fetch a tonic medicine for the poor child were surprised to find him still alive when they returned.

In due course, he was sent to school at Grantham. He did not make a good pupil, being inattentive, according to his own statement, and standing low in his class. But he showed a certain mechanical aptitude in his play, devising ingenious ways of measuring the speed of the wind, making clocks, sundials, and a working model of a windmill, and designing a carriage which was to go when its occupant turned a handle.

When he was thirteen, his mother lost her second husband and Newton was called home to help on the farm. But it soon became clear that his interests lay elsewhere, and that he gave more thought to mechanical problems than to agriculture. Finally, it was decided that he would never make a good farmer so he might try to be a scholar. He was sent to Trinity College in Cambridge, the college where his uncle had been educated, probably entering in June, 1661.

There is no evidence that he was especially interested in science at this time, or that he especially impressed the college authorities by his ability. A book on astrology seems to have been more effective than they in awakening his interest in science. In it, he found a geometrical diagram which he could not understand; he then bought a Euclid and set to work to learn geometry. Having mastered this book with ease, he went on to study the far more difficult Geometry of Descartes, which seems to have given him a real interest in mathematics and a taste for science.

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* Sir James Jeans, The Growth of Physical Science, (New York: Fawcett, 1967), pp. 167-168, 172. Used by permission.

INVESTIGATION 7: THE LAWS OF MOTION

In the summers of 1665 and 1666, England was ravaged by the plague and the Cambridge students were sent home to avoid infection. In the quiet of Woolsthorpe, Newton found leisure to ponder over many of the scientific problems of the day and made good progress towards the solutions of many of them. Writing of this some fifty years later**, he said: "In the beginning of the year 1665, I found the method for approximating series, and the rule for reducing any dignity (that is, any power) of any binomial to such a series.+ The same year, in May, I found the method of tangents of Gregory and Slusius, and in November, had the direct method of fluxions,++ and the next year, in January, had the theory of colors, and in May following, I had entrance into the inverse method of fluxions (that is, the integral calculus), and in the same year (1666), I began to think of gravity extending to the orb of the moon, and ...from Kepler's Rule of the periodic times of the planets, I deduced that the forces which keep the planets in their orbits must be reciprocally as the squares of their distances from the centers about which they revolve; and thereby compared the force requisite to keep the moon in her orbit with the force of gravity at the surface of the earth, and found them equal pretty nearly. All this was in the two plague years of 1665 and 1666, for in those days I was in the prime of my age for invention, and minded mathematics and philosophy more than at any time since." Thus, before he was twenty-four years old, he had already thought out a program for a large part of his life's work.

** In a MS. quoted in the preface to "A Catalogue of the Newton MSS.", Portsmouth Collection (Cambridge, 1888), p. viii. This MS. was probably written in or about the year 1716.

+ This is the famous binomial theorem. See p. 202.

++ This is the differential calculus, the most famous and the most important of Newton's mathematical discoveries.

INVESTIGATION 7: THE LAWS OF MOTION

Newton's tastes and interests all seem to have been of an intensely serious kind. He must have been quite devoid of humor and seldom laughed or joked. In the only known instance of his laughing (recorded twice, see Brewster's Memoirs, II, 91). Newton did not laugh with a friend, but at him--because he could not see the use of learning Euclid. The catalogues of Newton's books and furniture made after his deatn suggest that he had no pleasure or interest in art, music, literature, or poetry (Villamil, Newton the Man), and he appears to have been equally uninterested in country life, animals, exercise, sports, and games, both indoor and outdoor. He was ultra-careless about his dress and food. He never married, and one boy-and-girl affair seems to have been the sum total of his interest in the other sex. It may be that his intense intellectual efforts left him with but little mental energy for more human interests, and often with but little even for his science.

READING B: LAWS OF MOTION*

Note: These are the well-known laws of motion which form the starting point of every argument in classical dynamics. The first two laws, which relate to inertia, were generalizations from Galileo's observations. The first law, usually known as the law of inertia, is clearly a special case of the second.

Law I

Every body perseveres in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed thereon.

Projectiles persevere in their motions, so far as they are not retarded by the resistance of the air, or impelled downwards by the force of gravity. A top, whose parts by their cohesion are perpetually drawn aside from rectilinear motions, does not cease its rotation otherwise than as it is retarded by the air. The greater bodies of the planets and comets, meeting with less resistance in more free spaces, preserve their motions both progressive and circular for a much longer time.

Law II

The alteration of motion is ever proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

If any force generates a motion, a double force will generate double the motion, a triple force triple the motion, whether that force is impressed altogether and at once, or gradually and successively. And this motion (being always directed the same way with the generating force), if the body moved before, is added to or subducted from the former motion, according as they directly conspire with or are directly contrary to each other; or obliquely joined, when they are oblique, so as to produce a new motion compounded from the determination of both.

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* Isaac Newton, Mathematical Principles of Natural Philosophy, trans. by A. Motte, ed. by F. Cajorie (Berkeley: University of California, 1947). (Used with permission of the author and publisher.)

Notes by Morris H. Shamos, Great Experiments in Physics, (New York: Holt, Rinehart and Winston, 1959), pp. 52-53.

Note: By alternation of motion, Newton had in mind rate of change of momentum. For the case of constant mass, this becomes F=ma. Thus, the second law provides a definition of force in terms of the acceleration given to a mass.

Law III

To every action there is always opposed an equal reaction: or the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

Whatever draws or presses another is as much drawn or pressed by that other. If you press a stone with your finger, the finger is also pressed by the stone. If a horse draws a stone tied to a rope, the horse (if I may say so) will be equally drawn back towards the stone: for the distended rope, by the same endeavor to relax or unbend itself, will draw the horse as much towards the stone, as it does the stone towards the horse, and will obstruct the progress of the one as much as it advances that of the other. If a body impinge upon another, and by its force change the motion of the other, that body also (because of the equality of the mutual pressure) will undergo an equal change, in its own motion, towards the contrary part. The changes made by these actions are equal, not in the velocities but in the motions of bodies; that is to say, if the bodies are not hindered by any other impediments. For, because the motions are equally changed, the changes of the velocities made towards contrary parts are reciprocally proportional to the bodies. This law takes place also in attractions.

INVESTIGATION 7: THE LAWS OF MOTION

Note: The third law was original with Newton, and is the only physical law of the three. Taken with the second, it serves to describe the concept of mass in terms of its inertial properties. Mass cannot be defined explicitly but rather described in terms of its inertial and gravitational properties, which means that it cannot be described independently of the concept of force. Newton spoke of mass as the quantity of matter in a body, which lacks precision because we have no definition of matter. The first two laws are better considered as definitions (of force); the first describes the motion of body in equilibrium while the second describes its motion when the forces acting upon it do not balance one another.

READING C: ROCKETS*

How Rockets Work

A basic law of motion--discovered in the 1600's by the English scientist Sir Isaac Newton--describes how rockets work. This law stated that for every action, there is an equal and opposite reaction. Newton's law explains why the flow of air from a toy balloon propels (drives forward) the balloon in flight. A powerful rocket works in much the same way.

A rocket burns special fuel in a combustion (burning) chamber and creates rapidly expanding gas. This gas presses out equally in all directions inside the rocket. The pressure of the gas against one side of the rocket balances the pressure of the gas against the opposite side. The gas flowing to the rear of the rocket escapes through a nozzle. This exhaust gas does not balance the pressure of gas against the front of the rocket. The uneven pressure drives the rocket forward.

The flow of gas through the nozzle of a rocket is the action described in Newton's law. The reaction is the continuous thrust (pushing force) of the rocket away from the flow of exhausting gas.

Rocket Propellant

Rockets burn a combination of chemicals called propellant. Rocket propellant consists of (1) a fuel, such as gasoline, kerosene, or liquid hydrogen; and (2) an oxidizer (a substance that supplies oxygen), such as nitrogen tetroxide or liquid oxygen. The oxidizer supplies the oxygen that the fuel needs to burn. This supply of oxygen enables the rocket to work in space, which has no air.

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* Wernher von Braun and Frederick I. Ordway, "Rocket", World Book Encyclopedia, (Chicago: Field Enterprises, 1977), 16, pp. 357, 360-360A. (Used with permission of the author and publisher.)

INVESTIGATION 7: THE LAWS OF MOTION

Jet engines also work by means of an action-reaction process. But jet fuel does not contain an oxidizer. Jet engines draw oxygen from the air and, for this reason, cannot function outside the earth's atmosphere.

A rocket burns propellant rapidly, and most rockets carry a supply that lasts only a few minutes. But a rocket produces such great power that it can hurl heavy vehicles far into space.

A rocket burns the most propellant during the first few minutes of flight. During that time, the rocket's speed is held down by air friction, gravity, and the weight of the propellant. Air friction drags on the rocket as long as the rocket travels through the atmosphere. As the rocket climbs higher, the air becomes thinner and the friction decreases. In space, no air friction acts on the rocket. Gravity pulls a rocket toward the earth, but the pull decreases as the rocket travels farther from the earth. As a rocket burns its propellant, the weight it must carry becomes less.

READING D: MASS vs. WEIGHT*

It is easy to confuse the two ideas of mass and weight. This is because mass and weight are directly proportional to each other. That is, if the mass of an object is doubled, its weight is also doubled. If the mass of an object is halved, its weight is halved. But there is a distinction between the two. We can define each as follows.

Mass: The quantity of matter in a body. More specifically, it is the measurement of the inertia or sluggishness that a body, in the absence of friction, exhibits in a response to any effort made to start it, stop it, or change in any way its state of motion.

Weight: The force of gravitational attraction upon a body.

In the United states we commonly describe the quantity of matter in an object by its gravitational pull to the earth, or its weight. This is usually expressed in pounds. In most of the world, however, the measure of matter is commonly expressed in mass units, the gram or the kilogram.** At the surface of the earth, the mass of a 1 kilogram brick weighs 2.2 pounds. Away from the earth's surface, where gravity is less, a 1-kilogram brick weighs less. On the moon for example, where gravity is only a sixth as strong as earth gravity, 1 kilogram of mass weighs about 0.36 pounds. But the mass of the brick is the same everywhere. The brick offers the same resistance to speeding up, regardless of whether or not the earth, moon, or anything at all is attracting it. For example, in a space capsule located at a region between the earth and the moon, where gravities cancel one anoher, a brick still has mass.

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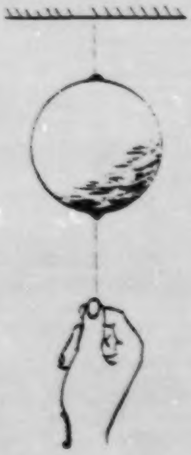
* Hewitt, Paul G., Conceptual Physics, A New introduction to Your Environment, (San Francisco: Little, Brown and Co., 1971) pp. 21-23.

** The system of measurement common in the United States is called the engineering system, in which the unit of mass is called the slug and the unit of force is called the pound. Most other parts of the world use the metric system, in which the unit of mass is the gram or kilogram and the unit of force is correspondingly called the dyne or newton.

INVESTIGATION 7: THE LAWS OF MOTION

If placed on a scale the brick wouldn't weigh anything, but its resistance to a change in motion is the same as on the earth. Just as much force would have to be exerted by an astronaut in the space capsule to shake the brick back and forth as would be required to shake it back and forth while standing on earth. It would be just as hard to push a Cadillac across a level surface on the moon as on earth. How hard it is to get an object moving is one thing and how much it weighs is something else. Mass and weight are different from one another.



Why is it that a slow continuous increase in the downward force breaks the string above the massive ball, but a sudden increase breaks the lower string?

Name________________________

Section______________________

Introduction

You now have Newton's three Laws of motion to use in solving problems involving motion in a straight line. You can predict what will happen to an object when no unbalanced force acts on it. You can predict what will happen to a body when a net unbalanced force acts on it in a direction either with or against its motion. You also know that forces always occur in equal and oppositely directed pairs. In addition, you have the motion equations from Investigation 1 that describe straight line motion. But what about motion in a circle? How can you explain that? You will study circular motion in Investigation 8.

Exploration

Cover the glass tube in the apparatus you are given with masking tape to prevent breaking it. Leave the two ends uncovered. String the fishline or long thread through the glass tube. Check to see that the thread is free to move in the glass tube. Attach one end of the thread to a 100 g mass (0.10 kg). Now attach the rubber stopper to the free end of the thread. Your equipment should now have the appearance of the drawing below:

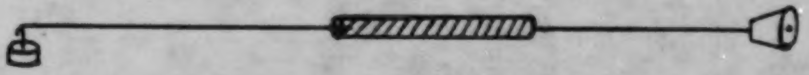


Figure 1

Holding the tape-covered glass tube in one hand, grasp the 100 g mass in the other and begin swirling the tube so that the stopper begins moving in a circle. Below is a drawing of what you should see as you are twirling the stopper. Be sure the stopper's motion is perfectly horizontal (parallel to the ground).

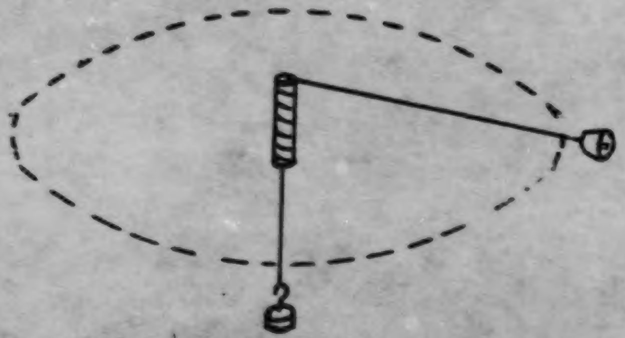


Figure 2

Increase the speed of the stopper until you can release the 100 g mass without observing it move up or down.

1. Find the force acting downward on the 100 g mass. Show your equation, work and units.

2. If the 100 g mass is not moving up or down, what net force is acting on it?

3. If there is a force acting downward on the mass (due to gravity), how can you explain the condition you described in Question 2?

4. What could be the source of the force you described in Question 3?

Remove the mass and hold the end of the string in one hand while using the other hand to twirl the tube. When the stopper reaches the point in the circle directly in front of you, release the string. Try this several times. Each member of the group may wish to try it.

5. Where does the stopper land in relation to the point at which it was released?

6. What explanation could you give for the data you recorded in Question 5? Try to use your knowledge of Newton's laws of motion in your explanation.

Name______________________________

Section____________________________

The Idea

1. When the mass is not rising or falling and the radius of the circle made by the stopper is not changing, how do the forces acting on the 100 g mass and on the stopper compare?

____

____

Explain your answer based on the data you have taken so far.

____

2. What force is acting downward on the 100 g mass? (Describe it and give its value in newtons.)

____

____

3. When the radius of the circle made by the stopper is not changing, what amount of force must be acting on the stopper to keep it moving in a circle?

____

____

4. What is the direction of the force you described in Question 3?

____

____

____

Name__________________________

Section__________________________

Expansion of the Idea

Part 1: An Experiment

This portion of Investigation 8 will be directed toward finding relationships among variables involved with circular motion. Our goal is to find a way to determine the centripetal force from information about the circling body.

A. Finding the relationship of the speed of the circling body to the centripetal force when the radius of the circle and mass of the stopper are held constant.

You will find the speed of the circling stopper (keeping the radius constant) for various values of centripetal force set by changing the mass on the string.

1) Lay the glass tube, string, mass and stopper apparatus on the laboratory table. Adjust the string so that the distance between the top of the glass tube and the middle of the rubber stopper (with the string taut) is 0.75 meter. When the 0.75 m distance has been established above the glass tube, fasten a piece of masking tape to the string just below the bottom of the tube (but not touching). When whirling the apparatus, the tape will always be right at the bottom of the tube when the radius of the circle in which the stopper is rotating is 0.75 m.

Hold the 0.100 kg mass in one hand and hold the glass tube with the other. Again revolve the glass tube at a speed that will make the rubber stopper travel in a circle. Now adjust the speed of the stopper until the tape is just below the bottom of the glass tube, so that the radius of the circle is about 0.75 m. Practice keeping the tape in place so that a constant radius is maintained.

You are going to measure the amount of time required for 10 revolutions of the stopper while the tape is kept just below the bottom of the tube. One member of your group will rotate the tube and keep the tape in place. The other members of your group will measure the time (using a stopwatch) and count the number of revolutions. Be sure to practice with the apparatus before collecting your data.

The time required for the number of revolutions you are measuring should be measured twice. (If the two times you measure are different by more than 5%; take a third time measurement.)

2) You will need to take the data necessary to complete Table I.

Table I

Constants: Radius 0.75 m; mass of stopper _____

Hanging Mass (kg)	Centripetal Force (N)	Time for 10 Revolutions (sec)			Period (sec)	Speed of Stopper (m/sec)
		1	2	Avg		
0.100						
0.120						
0.150						
0.170						
0.200						

3) How will you determine the centripetal force on the stopper?

4) How can you determine the period (the time for one revolution) from the time for 10 revolutions?

5) How can you determine the speed of the stopper using the radius of the circle and the period?

6) Make a graph of the centripetal force in newtons against the speed of the stopper (v) in m/sec. Put the speed (v) on the vertical axis and the force on the horizontal axis.

a. Describe the resulting graph.

____

____

b. Now make a graph of the centripetal force in newtons on the horizontal axis against the speed of the stopper squared (v^2) on the vertical axis. Describe your graph.

____

____

c. What relationship between the speed of the stopper (v) and the centripetal force, F_c, is suggested by your graphs?

____

____

B. Finding the relationship between the speed of the circling body to the radius of the circle when the centripetal force is held constant.

Lay the circular motion equipment on the table and mark with pieces of tape (or by some other means), spots on the string just below the glass tube that will give radii of 1.5 m, 1.0 m, 0.75 m, and 0.50 m. Using 0.100 kg as the hanging mass, gather the data necessary to complete Table II.

TABLE II

Constants: Hanging Mass=0.100 kg;
Stopper Mass ______

Radius (M)	Time for ______ Revolutions (sec)			Period (sec)	Speed of Stopper (m/sec)
	1	2	Avg		
1.50					
1.25					
1.00					
0.75					
0.50					

1) Make a graph of the radius in meters against the speed of the stopper (v) in m/sec. Put the speed (v) on the vertical axis and radius (R) on the horizontal axis. What relationship between v and R is suggested by your graph?

____

____

2) Now make a graph of the radius in meters against the speed of the stopper squared (v^2) in m^2/sec^2. Put v^2 on the vertical axis and radius (R) on the horizontal axis. What relationship between v^2 and R is suggested by your graph?

____

____

____

C. Finding the relationship between the speed of the circling body and its mass when the radius and the centripetal force are held constant.

Attach one stopper to the circling end of the string and a 0.400 kg mass to the other end. You will need to measure the time it takes to circle the stopper at a radius of 0.50 m for ten complete revolutions. Take that time measurement twice. If those time measurements are not about the same, take a third measurement. Record your data in Table III below. (Important: Keep the path of the motion of the stopper parallel to the floor!)

Table III

Constants: Radius 0.50 m; Centripetal force=_______

Number of Stoppers	Stopper Mass (kg)	Time for 10 Revolutions (sec)			Period (sec)	v (m/sec)				
		1	2	Avg						
1										
2										
3										
4										
5										

Now repeat what you just did with two stoppers of the same size, material, and number of holes. Continue increasing the number of stoppers until you have taken data with five stoppers on the string. Now measure the mass of each set of stoppers and record the measurements in Table III.

1) Make a graph of the speed in meters/second against the stopper mass in kilograms. Put the speed (v) on the vertical axis and the mass (m) on the horizontal axis. What information about the relationship between the speed of the stopper and its mass is given by the graph?

2) Use the unfilled spaces in Table III to add data about v. For example, you may want to use the first empty space for v^2 in m^2/sec^2. Then graph v^2 vs m and see if you get a straight line that passes through the origin. You may want to add data about 1/v and graph 1/v against m. Keep adding data and graphing the relationships until you can find a straight-line graph that passes through the origin. (Be sure to attach your graphs to the Investigation 8 work that you turn in to your teacher for evaluation.) What relationship between v and m is suggested by your graphs?

D. The relationships among the variables.

In parts A, B, and C, you have found three relationships among the variables involved with circular motion. Write those relationships in the spaces provided below:

Part A: Constants: R, m; Relationship:

Part B: Constants: F_c, m; Relationship:

Part C: Constants: F_c, R; Relationship:

Your next task is to try to synthesize the three statements you made above into one statement that describes the relationship among the variables R, m, v, F_c. Discuss this with the other members of your group and write your synthesizing equation on the line below.

You will be discussing this relationship as a class. Be ready to present your synthesizing equation to the class and explain how you arrived at it. You may find it necessary to change your equation after hearing other groups present theirs. Your class and your teacher will decide on a final equation to relate the variables. Write the final equation for F_c in the space below.

What equation might you use to find F_c when you are not given the speed of the object, rather only the mass of the object and the radius and period of the circle?

In The Idea section you determined that an inward seeking, or directed, force was responsible for keeping the stopper moving in a circular pattern. You called this force centripetal force.

1) How do you know the centripetal force acting on the stopper was an unbalanced force? (Support your answer by using Newtons Laws of Motion.)

2) According to Newton's Second Law of Motion, what must be the result when an unbalanced force acts on an object?

3) What name would you give to the motion described in Question 2? Explain why you named it as you did.

4) What would be the direction of this motion? Explain your answer.

5) What equation might you use to solve for the a_c of any given object moving in a circular pattern?

6) Evaluate and respond to the following statement: "An object moving in a circular path may have constant speed and be accelerating at the same time." (Hint: recall what you learned in Investigation 2.)

Name________________________

Section________________________

Expansion of the Idea

Part 2: Problems

1. A merry-go-round with a diameter of 2.0 meters is being rotated by a child who has a mass of 20 kg. The child can run at a top speed of 1 meter/second. Holding on to the outer bars of the merry-go-round, the child runs until achieving top speed, then jumps on.

   a. Find the centripetal force acting on the child just after he jumps onto the merry-go-round.

   b. What is the direction of the force?

2. A car on a circular racetrack of radius 200 m has a constant speed of 20 m/sec. It has a mass of 1000 kg. Find the centripetal force acting on the car.

3. A jet plane flying at 800 miles/hour (355 m/sec) makes a circle with a radius of 2000 meters.

   a. Find the centripetal acceleration of the pilot.

   b. How does the centripetal acceleration compare with the acceleration due to gravity, 9.8 m/sec^2?

4. A boy is twirling a 1.0 kg stone by means of a 2.0 m long string. The stone has a period of 1.0 second. At some point on the circle the stone slips out of the loop in the string.

   a. What will happen to the stone? Support your answer.

   b. What will be the speed of the stone as it leaves the circle?

5. A man who has a mass of 100 kg is standing on the equator. What is the centripetal force on him due to the earth's rotation? (The radius of the earth at the equator is 6.378×10^{10}m.)

6. Find the centripetal acceleration on a rock imbedded in the tread of a tire. The rock has a mass of 50 g and the radius of its motion is 40 cm. The car is traveling at 100 km/hr (about 60 miles/hour).

7. A boy ties a 1.0 kg rock on to the end of a 3.0 meter rope and then swings the rope over his head in a circle. The period of the circular swing is 1.0 second.

   a. Find the force acting on the rock.

   b. What is its direction?

   c. What is the source of the force acting on the rock?

8. A satellite is in orbit around the earth at a distance of 200 km above the earth's surface. The mass of the satellite is 1000 kg and its period of revolution is 88.5 minutes. (The mass of the earth is approximately 5.96×10^{24} kg.)

   a. Find its centripetal acceleration.

   b. What force is responsible for this acceleration?

   c. What is the magnitude and direction of the force acting on the satellite?

Name________________________

Section______________________

Expansion of the Idea

Part 3: Reading Questions--Centripetal vs Centrifugal Force, and Frames of Reference

1. How did the student's teacher explain the motion of a circling body?

2. What problem did the student have with his teacher's explanation?

3. How did the student apply Newton's Third Law to circular motion?

4. How did the student finally explain his movement in the car?

5. What do you think about centrifugal force? Is it real or ficticious? Explain your answer.

6. How would one's frame of reference influence his thinking about centrifugal force? Explain your answer.

Name____________________

Section____________________

Expansion of the Idea

Part 4: Reading Questions--Free Fall Forever

1. In your own words describe why objects appear to float--or to be weightless--in space.

Expansion of the Idea

Part 5: Reading Questions--An Attractive Law

1. Use Newton's laws of motion to explain why it is reasonable to assume that the orbit of a planet is maintained by a center-directed force.

2. a. Calculate the weight of a 50 kg mass on the moon using Newton's Law of Universal Gravitation. (The mass of the moon is approximately 7.33 x 1022 kg; the radius is 1.738 x 10^6.)

b. Now calculate the weight of the 50 kg mass on the moon using the special case of Newton's Second Law you derived in Investigation 5.

c. How do your answers for (a) and (b) compare? Explain why you would or would not expect these results.

3. Alfred, a male aardvark, has a crush on Ardine, a female aardvark. Alfred moves close to Ardine; he is 1 meter away. If Alfred weighs 100 N and Ardine weighs 75 N, what is the attractive force between Alfred and Ardine?

INVESTIGATION 8: CIRCULAR MOTION

READING: CENTRIPETAL VS. CENTRIFUGAL FORCE

You are riding in your car down a straight stretch of road. Everything seems fine as you lazily daydream in the warm spring sun. "Everything is explainable," you say confidently. "The laws of physics so clearly explain the motions of everything, a ball being thrown, or dropped, a hockey puck standing still on the ice, or accelerating in proportion to the force exerted on it by a player's stick, moving in a straight line with a constant velocity after the player lets it go. Forces act in action-reaction pairs so the hockey player is accelerated backward as he pushed the puck forward. Wow? It feels great to know so much."

In your daydreaming, you forget to slow down for the sharp curve just ahead. You are able to slow down enough to keep the car on the road, but as you are turning you notice something. Something seems to be pushing you against the car door!

It takes you a little while to get over the scare of having to negotiate the turn at a higher than normal speed, but once you have convinced yourself that you will watch more carefully in the future and not daydream so much, the experience comes back to your thoughts again. "What was pushing me against the car door while I was turning? Pushes are forces and forces have causes, but what caused this force? Obviously it had to have something to do with my turning the car because the force did not exist while I was driving straight. Also, the force's direction seemed to be outward. What could cause an outward force acting only when I turn?"

As you continue driving, you think about the centripetal force investigation you just completed in physics class. "When an object moves in a circle (and a curve in the road could be seen as a partial circle) there must be a center-directed force pulling it out of straight-line motion," you say.

At this point, you see three cows grazing in the field next to the road and a hawk perching on a telephone pole. You don't know it, but you missed seeing three hawks in the past two miles. "Aw, who thinks about physics outside of class on a day like this! Forget the problem!"

But the problem will not go away. You can't help thinking about it. The force inward was centripetal force so from Newton's Third Law of Action-Reaction, the outward force must have been centrifugal force.

INVESTIGATION 8: CIRCULAR MOTION

You recall the lecture in physics class in which your teacher discussed centripetal and centrifugal forces. "There are two forces acting on the circling body," he said, "Centripetal force acts to pull the body inward, but Newton's Third Law of action and reaction requires that there be an outward force equal and opposite to the centripetal force which is called centrifugal force."

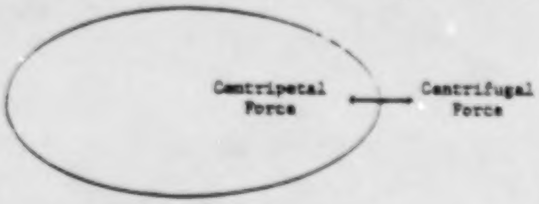


Figure 1

"I must have been experiencing centrifugal force when I was thrown to the side of the car on the curve," you say to yourself. "But wait a minute. If centrifugal and centripetal forces are both acting on the same object, they are equal and opposite forces so the net force should be 0 newtons and the circling object should be experiencing Newton's First Law motion which is motion at a constant speed in a straight line."

"Oh, dear. This is getting to be too much," you say. "Why don't I go back to watching the cows and the hawks." You see a hawk flying lazily over a field with two small birds flying alongside apparently pestering the hawk since occasionally the hawk appears to veer suddenly toward one of them as if to drive it off. But it is always to no avail; the small birds are much more manuverable and choose to stay with the hawk. Suddenly the hawk dives downward to the ground and you don't see it again, so you decide it must have seen, captured, and is now feasting on some prey with the little birds close by hoping for a free lunch.

"Who am I to disagree with my teacher, anyway," you think to yourself not realizing your thoughts have drifted back to the circular motion problem. "But how could Newton's Third Law apply to circular motion? The action and reaction forces don't have to be on the same body, in fact, they can't be if any acceleration is to occur. So what is the reaction force to the centripetal force and on which body does it act? Could it be that the reaction force is on the object being circled? It would be a force acting outward in the direction of the circling body. If that is the case, then the centripetal force is the only net force acting on the body moving in a circle. Centripetal force is then pulling it out of the straight line motion that Newton's Laws would prescribe for an object on which no net forces were acting. The opposite force then acts outward from the object in the center. So, when my car was traveling around the curve, it was being pulled out of straight line motion by forces acting betwmen the car and the ground. Each of the two front tires were interacting with the pavement to pull the car toward the center of the curve's circle. These forces were then acting as the centripetal force."

"But why did I move against the car door? Because even though the car was turning, Newton's First Law was acting on me. My inertia was keeping my motion in a straight line. The forces between me and the car seat were sufficient to bend my motion from straight-line motion, but not sufficient to keep me moving with the car. The car door came to my rescue and the centripetal force acting on the car was then acting on me also. So centrifugal force was not acting on me. In fact, there is no centrifugal force at all. The supposed force acting on me in the car is really my moving according to Newton's First Law while the car was accelerating inward by Newton's Second Law."

So there is no such thing as centrifugal force. It is not needed to explain circular motion. It is a ficticious force. You will, of course, have to check with physics textbooks and encyclopedias to find out whether they analyze the motion of an object moving in a circle the same way you have. If they disagree with you, find out their reasons. Feel free to disagree with them also, as you disagreed with your teacher, but do not become unwilling to change your mind just because the idea was your invention.

Go ahead and continue driving along the road. Watch the cows and hawks if you choose, or think about another problem that comes to your mind. But, make sure that you watch the road. Watch especially for the curves. You would not want the centripetal force needed to turn your car to be greater than the force available from the interaction of your tires with the pavement.

INVESTIGATION 8: CIRCULAR MOTION

READING: FRAMES OF REFERENCE

Life is full of paradoxes. A paradox is a statement which at first seems absurd or irrational, but which proves on reflection to be true or highly credible. One of the paradoxes in physics is related to circular motion. Physicists believe this statement: Motion in a circle at constant speed is accelerated motion. How can motion at a constant speed be accelerated motion? The key to understanding this apparent paradox is in the definition of the term vector. Since a vector quantity has both magnitude (amount) and direction, and since acceleration is a vector quantity, motion can be acceleration motion if either the speed or the direction change. Since in circular motion the direction is continually changing, the motion is accelerated motion.

Sometimes, physicists try to avoid absurdities in the physical world by viewing phenomena from different points of view, or as the physicist would call them, different frames of reference. Two walkers, both moving eastward at 2.0 miles per hour (mph), cover ground at different rates. That is absurd you say, until you discover that one is walking at 2.0 mph eastward on a train that is moving eastward at 50 mph. This is an example of a simple distinction between two different frames of reference. The walker on the train is walking at 2.0 mph eastward in the frame of reference of the passengers sitting on the train, and is covering ground at the rate of 52 mph eastward as viewed by observers outside the train.

Another example of changing frames of reference is that associated with an airplane flying in a wind. In this example, the airspeed may differ from the ground speed, again giving us two simple frames of reference, one with respect to the air and a second with respect to the ground.

The most important frame of reference with which physicists deal is one in which Newton's laws hold. Such a frame of reference is called an inertial frame of reference. A frame of reference in which Newton's laws do not hold is known as a non-inertial frame.

Motion of an object in a circle at constant speed may be viewed by an observer standing outside the system or by one riding on the circling object. The former provides an inertial frame of reference and the latter a non-inertial frame. If you are riding in a car, train, or airplane traveling in a circular path, you are in a non-inertial or accelerating frame of reference.

INVESTIGATION 8: CIRCULAR MOTION

An object traveling in a straight line has its path altered to a circular path by the action of a constant force acting on it at right angles to its motion which is always directed toward the center of the circle. This center-seeking force is called a centripetal force. To the observer outside the system in which the circular motion is taking place, this is all the explanation that is needed. To that outside observer, Newton's laws hold in the system so it is an inertial frame of reference. On the other hand, an observer riding in the system in which circular motion is taking place is confronted with a paradox.

Imagine yourself to be the passenger in a car which is traveling around a circular curve, the driver being on the inside of the curve. You try to leave the curve on a tangent but the outside door of the car keeps pushing you toward the center of the car and circle. Now, since you believe that all unbalanced forces cause accelerations, you expect the center-seeking force exerted on you by the door of the car to move you toward the driver, but it doesn't. You therefore reason that there must be a force directed on a radius of the circle outward which counterbalances the center-seeking or centreipetal force. You name this force centrifugal force. But centrifugal force is not a real force--it is a fictitious force invented by you to make Newton's laws hold in a non-inertial frame of reference. All accelerating frames of reference are non-inertial frames of reference. Accelerating frames of reference introduce special conditions which can often be best described by inventing fictitious forces. This is necessary only for the observer found inside the accelerating frame of reference trying to make Newton's laws apply to the system.

There are other situations in which scientists invent fictitious forces, but they are rare. However, the concept of frames of reference is a useful idea employed very frequently in physics. It assists us in understanding what otherwise might seem paradoxical. Looking at something from a different point of view or frame of reference is also helpful in everyday activities. If we could see events and problems from the frame of reference of others as well a from our own, or be empathetic, this would be a much better world.

INVESTIGATION 8: CIRCULAR MOTION

READING: FREEFALL FOREVER*

In Figure 1, two golf balls were dropped from a height close to the ground. Suppose a ball were dropped from a great height and given a large horizontal velocity, like the ball B in Figure 1. You know that the horizontal component of the ball's velocity tends to move the ball paralled to the earth's surfce. As the ball falls back toward the earth under the influence of gravity, it still possesses the horizontal component of velocity. The horizontal component allows the ball dropped from a great height to move over a large part of the earth's surface during its flight.

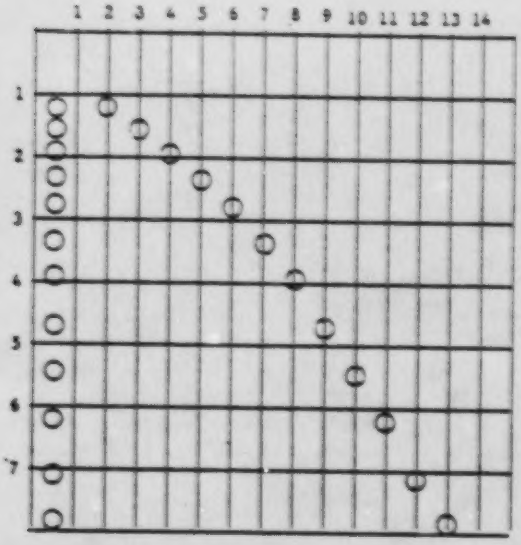


Figure 1. The two golf balls were released at the same time. Ball A on the left, falls freely, but ball B on the right was given an initial velocity of 2 m/s. What was the direction of the initial velocity given ball B? The time interval between photographs was 1/30 second and the horizontal lines are 15 centimeters apart.

Study Figure 2. The surface of the earth curves away beneath the falling ball, so that the ball travels farther to hit the earth than if the earth were flat. The greater the horizontal velocity, the farther the dropped ball will travel to the right. But the earth is not flat; it curves away from under the moving ball. A ball dropped with horizontal velocity $\vec{v}_{h2}$ does not travel a distance AB, it travels a distance AC. The greater the horizontal velocity $\vec{v}_h$, the farther the ball will travel. How large must $\vec{v}_h$ be for the ball to travel back around the earth to A? Let's find out.

INVESTIGATION 8: CIRCULAR MOTION

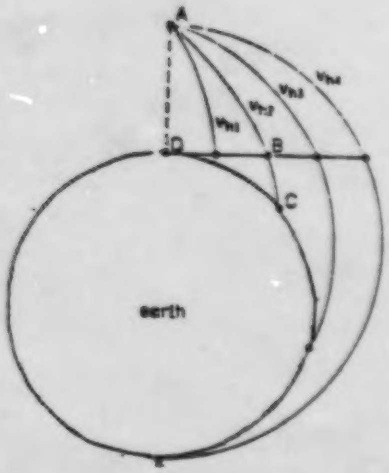


Figure 2. The greater the horizontal velocity, the farther the droped ball will travel to the right.

Imagine that a rocket carring a space capsule is launched into space. As the last stage of the engines that propelled the rocket into space drop away, thruster engines on the capsule are fired, giving it a horizontal velocity component. The capsule is also under the influence of gravity and has a vertical velocity component in the direction of the acceleration due to gravity. See Figure 3.

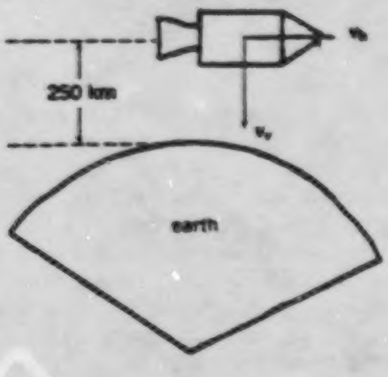


Figure 3. When a space vehicle reaches it desired altitude, it is turned parallel to the earth's surface. Its velocity at that instant, given it by the rockets that carried it, is also parallel to the earth's surface. So while being pulled toward the earth by gravity, it is also traveling over the earth's surface.

INVESTIGATION 8: CIRCULAR MOTION

What is the path of the capsule in space? Here is a problem in vector addition for you. The resultant velocity of the rocket has two components, one vertical and one horizontal—where horizontal means parallel to the surface of the earth. How can you find the resultant velocity? In more practical terms, how can the velocity components be chosen so that the capsule orbits parallel to the earth?

Here is another problem. You probably have seen pictures on television of astronauts in a free-fall orbit around the earth. If the astronauts or their cameras were not strapped down, you saw that they floated around inside the capsule. The reason that you may have heard given for that is that in a free-fall orbit, the capsule experiences zero-g--that gravity at the altitude of the capsule is zero, so it and its occupants are weightless. You ought to know better than that! And yet, the astronauts did float. Why did they? Does it have anything to do with the path in space of the orbiting capsule? Let's find out.

The value of the acceleration of gravity g at any point in the earth's gravitational field was found to be $g=g_0(1)/[1+(h/R_e)]^2$, where g_0 is the acceleration of gravity at the earth's surface, h is the distance above the earth where g is being measured, and R_e is the average radius of the earth. You know that the value of g_0 is 9.81 m/s^2. At a distance of 250 kilometers (150 miles) above the earth, where many orbitings occur, the value of g is $g=9.81\ m/s^2(1)/[1+(250\ km/6370\ km)]^2$; $=9.81\ m/s^2(1)/(1.039)^2$; $=9.81\ m/s^2/1.08$; $g=9.08\ m/s^2$.

A gravitational acceleration of 9.08 m/s^2 at 250 km above the earth's surface means that the acceleration is 7.4% less than the acceleration at the earth's surface. You know that the weight w of an object of mass m is proportional to the acceleration due to gravity g, or $w=mg$.

So the weight of the space capsule and its contents at an altitude of 250 km is decreased by 7.4%. But, it is not weightless. This calculation means that a space capsule orbiting the earth does have weight, and, as proof, the center of the capsule is constantly being pulled toward the earth's center. From Figures such as 1 and 4, you can conclude that the capsule is actually accelerated toward the earth and that it falls a certain distance toward the earth each second.

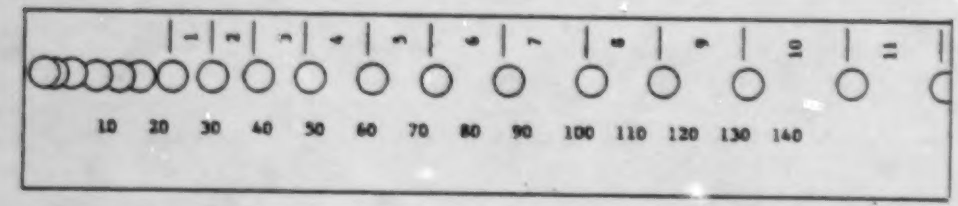

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Figure 4

Compare this situation with Figure 5 showing that the moon falls a distance h toward the earth during a certain time interval.

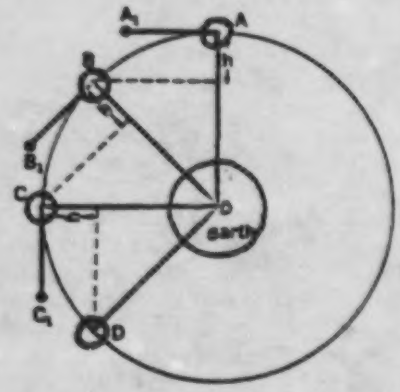
A₁
A
B
h
B₁
C
C₁
D
O
earth

Figure 5

There is, however, one important piece of information that has not been considered yet in detail. When the space capsule reached its 250 km altitude and was turned parallel to the earth's surface, it was given a horizontal velocity by the thruster rocket. Thus, while the spacecraft is being pulled down--accelerated toward the earth's center--it is also traveling over the earth's surface. The resultant velocity of the capsule can be resolved into two components, one parallel to the earth's surface and one toward the center of the earth.

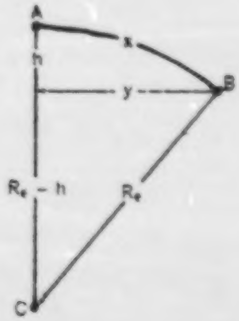

Figure 6

Imagine that you select a starting point A on the curved surface representing the earth shown in Figure 6 and travel in a straight line for a distance of one kilometer to B. The point you reach will be below your starting point by a certain distance h. This distance h is referred to as the earth's curvature per kilometer. Suppose a space capsule starts out directly above point A on the curved surface in Figure 6 and moves with a horizontal velocity toward point B. Since the curved surface is the earth, the capsule moving from A to B is also falling toward point C. Suppose the capsule takes the same amount of time to travel over the curved distance x (the distance from A to B) that would be necessary for it to fall the distance H. When it reaches point B it will be no closer to the curved surface than it was at A.

To remain in orbit around the earth, the capsule must travel across one kilometer of the earth's surface in the time it falls a vertical distance equal to the earth's curvature per kilometer h. If you know the earth's curvature/kilometer, you can calculate the time needed to fall such a distance. Knowing that time, you can calculate the capsule's orbital velocity because it must travel one kilometer over the earth's surface in exactly the same time it falls the vertical distance h. The first factor you must know, then, is the earth's curvature/kilometer.

Refer again to Figure 6 and use the Pythagorean theorem. $R_e^2 = y^2 + (R_e - h)^2$, or $h^2 + y^2 = 2R_e h$. The average radius of the earth R_e is 6370 km. Because x is only one kilometer, distance y must be slightly less than one kilometer. This means that h is much less than one kilometer.

Since the vertical distance h is much less than one kilometer, h^2 in the equation above becomes very small compared to the other quantities in the equation and can be eliminated. Using the above equation, the approximation for the curvature of the earth's surface per kilometer is written as: $h = (y^2)/(2R_e)$. To solve this equation for h, you need to know R_e and y. Refer again to Figure 6. The distance x across the curved surface of the earth is equal to one kilometer and R_e is equal to 6370 km. Comparing 6370 km to the one kilometer, you see that although y is smaller than x, there is so little difference between them that y is also approximately equal to one kilometer. Solving the equation with these approximations gives:

$$h = \frac{(1\ \text{km})2}{2(6370\ \text{km})}$$

$$= \frac{1}{12{,}740}\ \text{km}$$

(Converting km to cm) $$= \frac{100{,}000}{12{,}740}\ \text{cm}$$

$$= 7.85\ \text{cm}.$$

This answer can be interpreted to mean that the earth's curvature is approximately 8 cm per km. Once more, inspect Figure 6. You can see that a space capsule must travel one kilometer over the earth's surface while it falls a vertical distance of 8 cm. How long does it take a space capsule to fall 8 cm at an altitude of 250 km? The following equation relates distance and acceleration: $\triangle d = v_1 \triangle t = a(\triangle t)^2$. In this case $v_1 = 0$ and $a = g$, the acceleration due to gravity. You can write

$$t = \sqrt{\frac{2\triangle d}{g}}$$

INVESTIGATION 8: CIRCULAR MOTION

You calculated the acceleration due to gravity at an altitude of 250 km to be 9.08 m/sec^2, or 908 cm/sec^2. Using $d=7.85$ cm in the above equation, you find

$$\triangle t = \sqrt{\frac{2(7.85\ \text{cm})}{908\ \text{cm/sec}^2}}$$

$$= \sqrt{\frac{1}{57.8}\ \text{sec}^2}$$

$$= \frac{1}{7.60}\ \text{sec.}$$

To remain in orbit 250 km (150 mi) above the earth, then, a space capsule must travel one kilometer across the earth's surface in 1/7.60 seconds. The orbital velocity of the space capsule must be 7.60 km/s, which is 27,500 km/hr, or 17,000 mi/hr. Why is this only an approximate value?

Another way to think of the motion of the space capsule is as uniform circular motion. You calculated the acceleration due to gravity at 250 km to be 9.08 m/s^2. The radius of the orbit is the distance from the center of the earth plus 250 km, or 6620 km. Knowing the radius and the acceleration, use the equation $a_c=v^2/R$ to calculate the velocity. Which method of calculation do you think is more precise? Compare the assumptions made in the two calculations.

Thus, a space capsule falls around the earth. Because the radius of the earth used in calculation h, or $\triangle d$, was the average radius based on a spherical model of the earth, the orbit whose horizontal velocity must be 27,400 km/hr is a circular one. Because of the difficulty in aiming a rocket, this is a hard orbit to attain, and most space capsules and artificial earth satellites are in elliptical orbits.

INVESTIGATION 8: CIRCULAR MOTION

But what about those astronauts floating around in zero-g? The clue to the solution of the problem is that both they and their capsule are in free fall, just like the golf balls in Figure 1. Everything in the capsule is traveling in the same path and at the same speed as the capsule itself. The astronauts at 250 km are freely falling with an acceleration of 0.93 g_0, but so is the capsule. If you were in an elevator falling with an acceleration of 9.81 m/s^2 you would be weightless too--until you landed. But, if it were not for some small friction with the atmosphere, a space capsule in a circular orbit at 250 km could stay in free fall forever.

*John W. Renner and Harry B. Packard, Investigation in Physics, Lyon and Carnahan, Chicago, IL, 1974, pp. 86-90.

READING: AN ATTRACTIVE LAW

Sir Isaac Newton, who probably contributed as much to science as any other person, once declared in typical modesty that if he had discovered anything, it was because he was able to "stand on the shoulders of giants."

The story of the Law of Universal Gravitation starts with the ancient Greeks and ends with an apple. Newton is supposed to have thought of the final clue which led to his formulation of the Law of Universal Gravitation while watching an apple fall from a tree. (You will recall from an earlier reading that Newton spent contemplative time at his mother's farm when the plague struck London. At this time, Newton *supposedly* saw an apple fall from a tree and began to formulate his ideas concerning gravitational attractions and planetary interactions.)

The ancient Greeks were very interested in attempting to explain physical phenomenon--both earthly and heavenly. You will recall that Aristotle (384-322 B.C.) held that the fall of a heavy body toward the earth was its natural motion because *down* was the natural place for such a body. Heavier objects sought *down* more that lighter objects and, therefore, heavier objects would fall faster than lighter objects. This was Aristotle's way of explaining the results of the phenomenon we call gravity. We know now that Aristotle was wrong, that heavier objects do not fall faster than lighter objects when air resistance is negligible, but his idea appeared quite reasonable at the time.

Aristotle and his fellow Greek philosophers also attempted to develop a blueprint for the universe. First, the earth was positioned motionless at the center of the universe (this is called the *geocentric* view). The planets, the moon and the sun supposedly circled the earth. Second, the earth and the heavens were considered to be governed by different laws. The heavens were perfect, while the earth was...well, earthy. Since the heavens were perfect, they should be characterized by perfect motions. What could be more perfect than uniform circular motion? Thus, the planet's orbits consisted of perfect circles traversed at uniform speeds.

This view was to remain basically unchallenged until the time of Copernicus some 2000 years later. (It is interesting to note, however, that Aristarchus, 275 B.C., contended that the sun was the center of the universe and that the planets, including the earth, moved around the sun in large circular paths.) Nicolaus Copernicus (1473-1543), a Polish mathematician and astronomer, adopted a heliocentric (sun-centered) view of the universe. According to Copernicus, the sun was at rest at the center of planetary motion; the earth, the moon, and the planets revolved around the sun. The earth was not motionless, in fact, it had two motions--it revolved around the sun and it revolved around its own axis. Aristotle and his fellow philosophers had hypothesized that the earth could not turn lest the objects on the earth be thrown off into space. Copernicus did not press his ideas and he did not experience much opposition from the religious leaders of the Catholic Church, who were firmly rooted in Aristotelian cosmology. He did not assert the physical reality of his heliocentric theory.

One of the most brilliant astronomical observers rose to prominence several years after Copernicus' death. Tyco Brahe (1546-1601), a Dane, made meticulous observations using equipment he himself either invented or improved. The Danish King, Frederick II even provided Tycho with the funds to set up an extensive astronomy laboratory. Tycho made important observations concerning the comets, the planets, and the fixed stars. His observations concerning the retrograde motion of Mars have been found to be off by only a few degrees. One of Tycho's best discoveries was a young German mathematician named Johannes Kepler. When Tycho died in 1601, Kepler obtained all of his records and observations of the motion of Mars.

Kepler (1571-1630) was a Copernican--he was dedicated to perfecting the heliocentric theory. He used Tycho's observations of the motion of Mars as a starting point. He kept trying to squeeze circular orbits and the devises of other astonomers such as Ptolemy, Aristotle, and Copernicus (that is, equants and epicycles) into the data base gathered by Tycho. Kepler worked out the best system he could (after about seventy trials and a year and a half), but he discovered that his calculations diverged from Tycho's observations by eight minutes of arc. Eight minutes would be equivalent to about a fourth of the moon's diameter--which isn't much considering the equipment Tycho used.

Kepler had two choices at this point: he could throw out his system or consider Tycho's obsevations to be slightly erroneous. So sure of Tycho's expertise as an obsever was Kepler, that he determined that Tycho was right! Kepler then set out to come up with an entirely new system not based on uniform circular motion, equants, epicycles, or any other previously used devises. The results can be summarized in Kepler's three laws:

INVESTIGATION 8: CIRCULAR MOTION

1. Law of Elliptical Orbits: "The paths of planets are ellipses with the sun at one focus." The orbits were not circular, they were elliptical!

2. Law of Areas: "The line from a planet to the sun sweeps out equal areas per time." Simply put this means that a planet will move through the area AC in the same time it covers the area HK (see Figure 1).

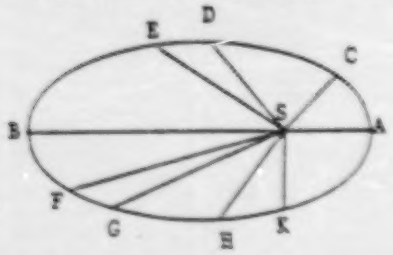

Figure 1

So much for uniform speed? This would indicate that a planet travels at a greater rate of speed the closer it is to the sun and at a lesser rate at greater distances from the sun.

3. Law of Periods: The ratio of the cube of the radius of the orbit to the square of the period for the planets is constant or $k=T^2/R^3$. Sure! Actually, all this means is that we can determine the period of the orbit of any planet if we know the radius of its orbit.

At this point, you might wonder why we are using radii while working with elliptical motions. The orbits of most of the planets are very nearly circular. Pluto's orbit is the most elliptical, while the orbit of Venus is very nearly circular. The orbit of the Earth is only a bit more elliptical than that of Venus. However, it would perhaps be more exacting to consider the average distance of the planet from the sun as being the value of R.

Thus, Kepler had revolutionized astronomy. Through the use of Tycho's observations and his own mahematical genius, Kepler had abolished the uniform circular motion of the ancients and replaced it with elliptical, non-uniform motion.

Galileo Galilei (1564-1642), the noted Italian scientist, corresponded with Kepler. Calileo was convinced of the validity of Copernicus' heliocentric view and spent much of his life trying to convince the religious leaders as well as the scientists of the time of its relevance. But Galileo's importance in our story deals with his work with terrestrial motion. Galileo determined that the weight of the object did not dictate the rate at which it would fall to earth. Galileo based his theories on empirical data and was more interested in the how's than the why's of free-fall.

INVESTIGATION 8: CIRCULAR MOTION

How can we work Newton and the Law of Universal Gravitation back into our story? Let's recall that Newton had an opportunity to spend two years pondering a multitude of problems while he was waiting for the plague to subside in London so he could return to his position at Trinity College at Cambridge University. One of his contemplations supposedly involved the fact that apples (and all other objects) fell perpendicularly to the ground--they never fell sideways or at an angle to the earth's center. But Newton did not stop here, he began to consider that the concept of gravity could be expanded to the motion of the planets as well as the motions of objects on earth. This was a revolutionary idea as the causes of physical phenomena on earth had long been considered separate from those of the heavenlies. Newton wrote:

> "I began to think of gravity extending to the orb of the moon, and...from Kepler's rule (third law, law of periods)...I deduced that the forces which keep the planets in their orbs must be reciprocally as the squares of their distances from the centers about which they revolve: and thereby compared the force requisite to keep the moon in her orb with the force of gravity at the surface of the earth and found them to answer pretty nearly. All this was in the two plague years of 1665 and 1666, for in those days (at age 21 or 22) I was in the prime of my age for invention, and minded mathematics and philosophy more than at any time since."

Newton found that motion in an elliptical path could only occur when the central force was an inverse square force--or $F \propto 1/R^2$. The matter was settled when Newton showed that such a force law would also result in Kepler's Third law ($k=T^2/R^3$). Let's look more closely at Newton's proof. You know from your work with circular motion that centripetal acceleration can be found using the radius of the revolution (or orbit, in the case of planets) and the period: $A_c=4\pi^2R/T^2$. Kepler's Law of Periods stated a definite relationship between the orbital periods of planets and their average distance from the sun: $K=T^2/R^3$ or $T^2=k \cdot R^3$. We can substitute $k \cdot R^3$ for T^2 in our equation for $a_c=4\pi^2R/k \cdot R^3=4\pi^2/k \cdot R^2$, since $4\pi^2/k$ is a constant, we can write $a_c \propto 1/R^2$. If we next consider Newton's Second Law of Motion, $F=ma$, we know that $F \propto a$. Thus, $F_c \propto 1/R^2$, and the quantity of the force exerted by the sun on a planet would be inversely proportional to the square of the radius of the planet's orbit.

INVESTIGATION 8: CIRCULAR MOTION

Newton concluded that one general Law of Gravitation applied to all bodies moving in the solar system--in fact, the law applied to any object moving in an orbit about a center of focus. Newton supposed that the planetary force was the same kind of force that caused objects near the earth's surface to fall. He first tested this idea on the earth's attraction for the moon.

According to the data available to Newton, the distance between the center of the earth and the center of the moon was about sixty times the radius of the earth (or $60 \times 6.378 \times 10^6$m). If the attractive force of the earth on the moon was proportional to the inverse of the square of the radius ($F_c \propto 1/R^2$, then the gravitational acceleration the earth exerts on the moon should be only $1/(60)^2$ or 1/3600 of that exerted upon objects at the earth's surface. You know from your laboratory work in Investigation 3, that the acceleration due to gravity at the earth's surface is about 9.8 m/sec/sec. Thus, the moon should fall toward the earth at 1/3600 of 9.8m/sec/sec (or 9.8/3600 m/sec/sec) or 2.72×10^3 m/sec/sec. Let's see how close Newton was.

The orbital period of the moon is approximately 27 1/3 days or 2.3×10^6 seconds. The radius of the moon's orbit around the earth is about 3.9×10^8 meters. Using the equation for centripetal acceleration, we can calculate the acceleration of the moon toward the earth.

$$a_c = \frac{4\pi^2 R}{T^2} = \frac{4(3.14)^2(3.9 \times 10^8 \text{ m})}{(2.3 \times 10^6 \text{ sec})^2} = 2.91 \times 10^{-3} \text{ m/sec/sec}$$

This is in very good agreement with the 2.72×10^{-3} m/sec/sec value predicted by Newton's idea that $a_c \propto 1/R^2$ and, thus, $F_g \propto 1/R^2$. Newton concluded that:

> "The force by which the moon is retained in its orbit becomes, at the very surface of the earth, equal to the force of gravity which we observe in heavy bodies there. And, therefore, the force by which the moon is retained in its orbit is that very force which we commonly call gravity..."

Thus, the same gravity that brings apples down to the ground also holds the moon in its orbit. How simple! But, how revolutionary!

INVESTIGATION 8: CIRCULAR MOTION

Newton's contemplations led him to believe that every object in the universe attracts every other object with a gravitational force. The sun attracts the earth, the earth attracts the moon and you, attract the person sitting next to you. (Cozy isn't it!)

One last step needs to be taken before we can state Newton's Law of Universal Gravitation in mathematical terms. Your work with circular motion showed you that centripetal force was proportional to the mass of the orbiting object or $F_c \propto m$. Since, according to Newton's hypothesis, every object exerts a gravitational force on every other object (and since that force must be equal in magnitude), it follows that the gravitational attraction between two bodies is proportional to the product of their masses (or $F_g \propto \text{mass}_1\ \text{mass}_2$). Combining this relationship with $F \propto 1/R^2$, we have:

$$Fg \propto \frac{\text{mass}_1\ \text{mass}_2}{R^2}$$

We can write this as an equation by introducing a constant, G. G is the gravitational constant. Thus, $F_g = G(m_1 m_2)/(R^2)$. This equation should apply to two gnats, two people, or two stars.

The value of G presented a problem until Henry Cavendish (1731-1810), an English scientist, devised an instrument for determining the gravitational attraction between two pairs of lead spheres. Cavendish employed a sensitive instrument called a torsion balance. In this devise, the gravitational attraction between the two pairs of lead spheres twisted a wire holding up one of the pairs. The twist of the wire could be measured against the twist produced by known forces. An experiment involving a 100 kg sphere and a 1 kg sphere at a center-to-center distance of 0.1 meter produced a force of 10^{-6}N. From these data the value of G could be calculated:

$$F_g = G\frac{m_1 m_2}{R^2}\ ;\ g = \frac{F_g R^2}{m_1 m_2} = \frac{(10^{-6}\ \text{N})(0.1\ \text{m})^2}{(100\ \text{kg})(1\ \text{kg})} = 10^{-10}\ \text{N}\cdot\text{m}^2/\text{kg}^2$$

The present accepted value of G is very close to this early calculated value: $G=6.67\times10^{-11}\ N\cdot m^2/kg^2$.

Whew! What a story! We have traveled from the third century B.C. to the middle of the eighteenth century A.D. What is the relevance of such a search? Newton's Law of Universal Gravitation was revolutionary in that it coordinated the physical laws of earth and the heavenlies. It shows us that the same forces that cause objects to fall toward the center of the earth also hold planets in their orbits. Finally, it has reduced that mysterious phenomenon called gravity to the interaction between masses. It is important to remember that Newton, like Galileo, was primarily interested in the *how's* not the *why's*. The *why's* of gravitational attractions are yet to be adequately explained. Perhaps you will finish the story.

INVESTIGATION 9: GRAVITATIONAL ATTRACTION STUDENT GUIDE

Name______________________________

Section____________________________

Introduction

You now have an idea of Newton's three laws of motion and how they work together to describe the motions of objects we are familiar with, particularly objects near the earth's surface where we live. You also have invented the concept of centripetal force that produces a centripetal acceleration on masses that move in circles. We will use these ideas to help you gather data about gravitational attraction.

You have seen evidence that objects are constantly accelerated toward the center of the earth by the force of gravity. But whether you realized it or not, all the cases you have been considering were near the surface of the earth. How does gravity affect objects that are not near the earth's surface? You probably know that the moon travels in a nearly-circular orbit around the earth. The radius of the moon's orbit is 384,000 km. That distance tells you the moon is not near the earth's surface. Since the moon is circling the earth, it has to be under the influence of centripetal acceleration. What causes that centripetal acceleration? This investigation will lead you to find out.

Exploration

Here are some data about the earth-moon system.

Moon: Average orbital radius
384,000 kilometers

Period: 27.3 days
Mass: (M_m) 7.4x10^{22} kilograms

Earth: Radius 6370 kilometers
Mass: (M_e) 6.0x10^{24} kilograms

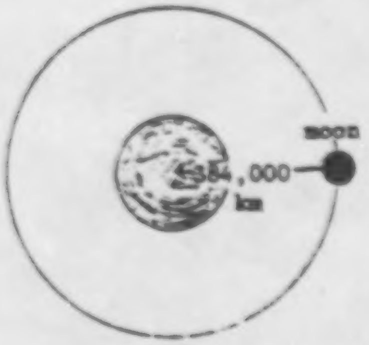

Figure 1

1. Study the above information about the earth and the moon. Find the moon's speed (in m/sec) as it moves around the earth.

2. Now find the centripetal acceleration of the moon toward the earth.

3. Assume for now that the earth's gravity which is responsible for the acceleration of an object near the earth's surface is also responsible for the centripetal acceleration of the moon. What is the acceleration of an object toward the earth when it is near the earth's surface?

4. Find the ratio of the two accelerations you just described.

$$\frac{a_g \text{ (surface)}}{a_c \text{ (moon)}} =$$

5. Now find the ratio of the two radii involved.

$$\frac{\text{Radius of the moon's orbit}}{\text{Radius of the earth}} = \frac{R_m}{R_e} =$$

INVESTIGATION 9: GRAVITATIONAL ATTRACTION STUDENT GUIDE

Name____________________________

Section__________________________

The Idea

1. Compare the two ratios you just made. How could you change one of the ratios to make them equal numerical values? Notice that

   $$\frac{a_g(s)}{a_g(M)} \neq \frac{R_m}{R_s}$$ Where $\neq$ means is not equal to.

2. Once you have determined how to make the two terms equal, write your revised equation in another form and record that equation here.

3. What is the significance of the statement you just made? Look again at the diagram of the earth-moon system if you need to.

4. Suppose a satellite were placed in orbit around the earth between the earth and the moon. How would you expect the value of a_gR^2 to compare with those you made earlier?

   What if the satellite were placed beyond the moon, how would the value of a_gR^2 compare with the others?

5. What do you know about the value of the product a_gR^2 at any distance from the earth's surface?

6. What does the information you have just gathered suggest to you about your assumption of Question 3 in the Exploration section that the gravitational acceleration of objects near the earth and the centripetal acceleration of the moon toward the earth are caused by the same force, namely gravity?

7. Find the value of the constant that is implied in the above statement. Show your work and show the units of the constant.

Name_______________________________

Section______________________________

Expansion of the Idea

Part 1: Problems

Weather satellites are often placed in stationary orbit 22,000 miles above the earth's surface. Stationary means that their position in the orbit over some selected part of the earth is stationary. Therefore a satellite placed over the United States can photograph the United States day or night.

1. On a sheet of paper, let 1.0 cm represent 1000 miles. At the left end of the sheet use a compass to draw a semicircle to represent an earth hemisphere of radius 4000 miles.

2. Now draw a partial circle to represent the orbit of the weather satellites. Determine the acceleration due to gravity of the weather satellites (Conversion: 1.0 kilometer=0.62 miles) and record it on the orbital line you have drawn.

3. Draw a partial circle to represent an orbital radius of 13,000 miles. Determine the acceleration due to gravity of such a satellite and record it on the orbital line you have drawn.

4. Draw a partial circle to represent an orbital radius of 6500 miles. Determine the acceleration due to gravity of such a satellite and record it on the orbital line you have drawn.

5. Draw a partial circle to represent an orbital radius of 3250 miles. What physical impediments might this satellite encounter?

Name____________________________

Section____________________________

Expansion of the Idea

Part 2: Graphing the Gravitational Attraction

You found earlier in this course that the acceleration due to gravity 4000 miles from the earth's center is 9.80 m/sec^2.

1. Apply the inverse-square law to find the acceleration due to gravity at each of the following distances:

   a. 8,000 miles

   b. 16,000 miles

2. Make a graph of gravitational acceleration against distance from the earth's center. Put gravitational acceleration on the vertical axis and distance from the earth's center on the horizontal axis. Combine the information on this page with that from Expansion of the Idea, Part 1, to make the graph.

3. Describe what the graph shows about the change in the acceleration due to gravity as the distance from the center of the earth increases.

4. Earlier in this course in the reading for Investigation 3, Falling Objects, we agreed that the acceleration due to gravity is a constant 9.8 m/sec^2. How do you interpret the meaning of that statement in light of the information you now have?

Name______________________________

Section____________________________

Expansion of the Idea

Part 3: Jupiter and Ganymede

Will the idea you invented earlier in this investigation also explain the motions of other heavenly bodies? To find out, you can work with the system of the planet Jupiter and Ganymede, one of its moons. Observation has provided the information given below.

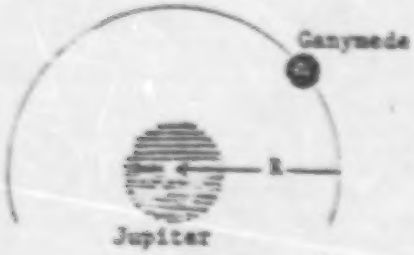

Figure 2

Ganymede: Average orbital radius 1.07×10^6 kilometers

Period: 7.15 earth days

Mass: $2M_m$

Jupiter: Mass: $320M_e$

1. Using the equation you invented in The Idea section of this investigation, and the value of the constant, K, predict the acceleration due to gravity of Ganymede toward Jupiter.

2. Now find the actual centripetal acceleration of Ganymede toward Jupiter using the motion equations, $a_c = v^2/R$ where $v = 2\pi R/T$.

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3. How do the values for Ganymede's acceleration toward Jupiter compare?

   Find the ratio of the two accelerations,

   $$\frac{a_c\text{(actual)}}{a_g\text{(predicted)}} =$$

4. Based on the data available on this page what possible explanation can there be for the ratio you found?

5. What new variable will have to be placed in the equation $a_g = mK/R^2$ and how will it have to be included to make the a_g (predicted) equal to the a_c (actual)?

6. Write the new equation you have developed.

7. What units of mass are used in this equation?

8. How can you change the units of mass to kilograms?

   (Do it.)

9. Now rearrange the equation in Question 6 to solve for the new constant.

10. Find the value of the constant and show its units. (Give the new constant the symbol G for gravitational constant.)

11. Rearrange the equation in Question 9 again to solve for gravitational acceleration. Find the value for the acceleration due to gravity at the earth's surface using earth mass in kilograms and radius in meters.

12. How does your value for a_g at the earth's surface compare with our measured value of 9.80 m/sec^2?

13. Predict the acceleration of the earth due to the sun's gravity using your equation and the solar mass of 1.98×10^{30} kg and the earth's orbital radius of 1.49×10^{11} m.

14. Determine the centripetal acceleration of the earth toward the sun from the motion equations: $a_c = v_2/R$ where $v = 2\pi R/t$. Remember, the period of revolution is 365 days.

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15. How do the values of the earth's acceleration compare?

16. How wide an application would you expect your equation to have?

17. Apply Newton's Second Law, F=ma, to the equation you developed. Find an equation for the *force* of gravitational attraction between two bodies where one is in orbit around the other. Give the constant the symbol, G, for gravitational constant. (Is the mass in F=ma the same mass as in the equation you developed in Question 11?)

18. Under what conditions is the force in Question 17 present? (For example, does it apply only to objects when one is in orbit about the other?)

Name______________________________

Section____________________________

Expansion of the Idea

Part 4: Universal Gravitation Problems

1. Find the gravitational force between two 100 kg masses which are 1.0 meter apart at their centers.

2. A force of 1.0 N exists between two objects. One has a mass of 1000 kg. The distance between their centers is 1 kilometer. Find the mass of the other body.

3. a. How much gravitational force exists between two people whose bodies have masses of 50 kg and are 0.50 cm apart.

   b. How does this force compare in size with forces you have used in this physics class?

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4. a. Find the force of attraction between the earth and the moon.

   b. Between the moon and the sun assume the average lunar distance from the sun is the same as the earth's distance.

   c. How do the forces compare?

   d. What do the forces suggest about which the moon is orbiting, the earth or the sun?

INVESTIGATION 10: FRICTION

STUDENT GUIDE

Name________________________

Section________________________

Introduction

You know that Newton's First Law states that objects in motion will remain in motion unless they are acted upon by some force external to the moving object. You also know that when a bowling ball, for example, is started rolling, it eventually comes to rest. How is that observation possible when Newton's First Law is considered? This investigation will furnish data to allow you to answer the questions asked in this paragraph.

Exploration

Place one of the blocks flat on the laboratory table top, the floor, or some other horizontal surface. Slide the hook of the spring scale through the hook on the block, hold the ring on the spring scale and gently pull the block forward. Be sure the scale is parallel with the horizontal surface on which the block is resting while the block is being moved forward. Four different experimental situations are listed below.

1. Experimental Situation A.: The block's unpainted surface is contacting the top of the table.
2. Experimental Situation B.: The block's painted surface is contacting the surface of the table.
3. Experimental Situation C.: Glass is between the block's painted surface and the top of the table.
4. Experimental Situation D.: Oil is between the block's painted side and the glass.

For each situation, record the maximum scale reading after you begin pulling the block, but before the block moves forward. These data should be recorded in the Block at Rest column in Table I. Also, record the maximum scale reading while the scale is moving at a constant speed in the Block Moving column in Table I. Be sure to make three measurements for each experimental situation.

Table I

Experimental Situation	Block		Scale Readings					
			Reading 1		Reading 2		Reading 3	
	Number	Weight	Block at Rest	Block Moving	Block at Rest	Block Moving	Block at Rest	Block Moving
A								
B								
C								
D								
E								
F								
G								

Name____________________

Section____________________

The Idea

1. How much of the block's weight is the spring scale supporting when you pull the block horizontally?

2. How much of the block's weight is the table supporting?

3. Why does the spring scale show a reading?

Name______________________

Section____________________

Expansion of the Idea

Part 1: An Experiment

Return to the laboratory and add a 500 gram weight to the top of the block whose painted surface touches the table top. Use a spring scale and pull the block exactly as you did before. Call that Experimental Situation E and record the data in Table I. Next repeat the procedure you just did, but add a one kilogram weight to the block. Call this Experimental Situation F and record the data in Table I.

1. What do your data tell you?

Now, focus your attention on the Block at Rest data from Table I. You know that $F_f \propto W$. Find the results of dividing F_f by W for Experimental Situations A, B, C, D, E, and F. Record your results in Table II.

Table II

	Experimental Situation (Block at Rest)	F_f/W
A	Unpainted on Table	
B	Painted on Table	
C	Painted on Glass	
D	Painted on Oil on Glass	
E	Painted, 500 gm Weight added)	
F	Painted, 1 kg weight added	

2. Look at the F_f/W data from Experimental Situations B, E, and F. How do they compare?

3. How do the F_f/W computations from Experimental Situations A, C, and D compare?

4. What do these data tell you about the F_f/W ratio and the surfaces of the objects involved?

5. What name would you give the ratio of F_f/W?

Again, look at the data for Experimental Situations B, E, and F in Table II. Remember that these results were computed from the F_f and W data in the Block at Rest column in Table I. Copy the F_f/W data from Table II for Experimental Situations B, E, and F in Table III.

Now use the data from the Block Moving column for Experimental Situations B, E, and F. Divide F_f by W for each situation and record the results in Table III.

6. Compare the coefficient of friction computations from the Block at Rest and Block Moving columns. What do your data tell you?

Table III

		Coefficient of Friction	
	Experimental Situation	Block at Rest	Block Moving
B	Painted, no weight added		
E	Painted, 500 gm weight added		
F	Painted, 1 kg weight added		

7. What name would you give to the coefficient of friction from the Block at Rest column? From the Block Moving column?

8. What factors in your data collecting affected the magnitude of the coefficient of friction?

9. You know that F_f is proportional to the weight, W, if the object is moving over the surface, or $F_f \propto W$. How much weight presses down on the surface the block is moving over?

10. What is the angle between the force pressing together the block's surface and the surface over which it is moving?

11. What name would you give to the force that presses the surfaces together?

12. You know that $F_f \propto W$. Rewrite that proportionality using the idea of the force that presses the surfaces together in place of the variable W.

13. Write the equation for F_f you have developed in this investigation.

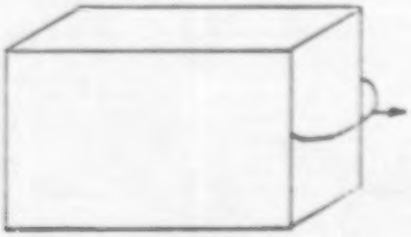

Figure 1

14. Repeat Experimental Situation A using one of the longer edges of the block rather than the bottom of the block against the table top. Call this Situation B. How do your data from Situation B compare with your data from Situation A?

15. What do your data tell you about surface area and F_f?

Name________________________

Section______________________

Expansion of the Idea

Part 2: An Experiment

In your data collection in the Exploration and Expansion of the Idea, Part 1 sections you kept the scale parallel with the surface and the surface level while pulling the block.

1. What do you think would happen to the scale reading if you pulled the block along while the scale was not parallel to the surface?

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2. How would the scale reading change if you were pulling the block up an incline?

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Begin by laying the plane or board flat on the table. Pull the block along the board surface holding the spring scale parallel to the surface as you did in the earlier parts of this investigation. Make and record in Table IV three measurements of the spring scale reading with the block moving at a constant speed. Next, with the board still flat on the laboratory table, pull the block along while the spring scale is perpendicular to the board surface as shown in Figure 2. Keep the block flat on the surface as you pull it with the spring scale. You may need to practice first. Record the data from the three trials in Table IV.

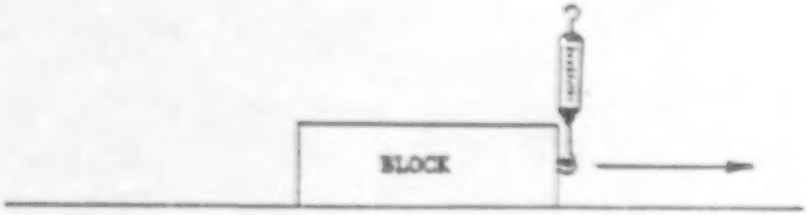

Figure 2

3. Compare the averages of the data from the two situations you just investigated. How would you explain any differences that may have occurred between the spring scale readings?

4. How did the normal force change when you pulled the block while the spring scale was perpendicular to the table top?

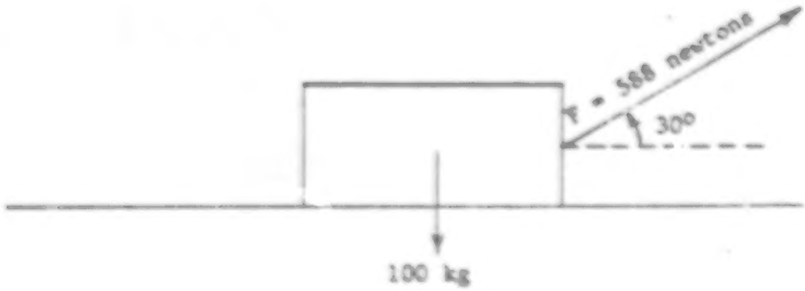

Figure 3

5. The block in the figure has a mass of 100 kg. It is pulled along the table surface by a rope which is at a 30° angle with the horizontal. Develop equations that would allow you to find (a) F_N and (b) F_F.

Now, elevate the board or plane so the surface is at about a 15° angle with the laboratory table. Pull the block up the incline at a constant speed keeping the spring scale parallel to the board surface (see Figure 4). Make and record three measurements in Table IV.

Table IV

		Block on Flat Surface	Block on Incline Surface			
Trial	Spring Scale Parallel to Surface	Spring Scale Perpendicular to Surface	15°	45°	60°	90°
1						
2						
3						
Avg.						

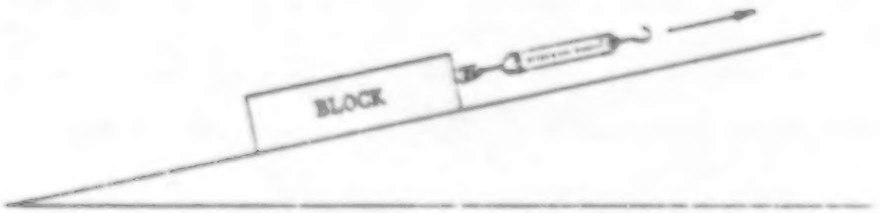

Figure 4

Repeat the measurements with the incline of the board at 45°, 60°, and 90° angles with the table surface. Record your data in Table IV.

6. How did the spring scale reading change as the angle of incline increased?

7. What explanation could you give for the change in the spring scale reading as the angle of incline increased?

8. How did the weight of the block change as the angle of incline increased?

9. How did the normal force change as the angle of incline increased?

10. If you had released the spring scale and the block had moved down the incline, what force would have been responsible for that movement?

11. How would the force that was responsible for moving the block down the incline change as the angle of the incline was increased?

12. How do you think the force of friction between the block and the board changed as the angle of the incline increased?

13. In the figure below draw and label the following vectors: pull force, gravity, force of friction, weight, and normal force.

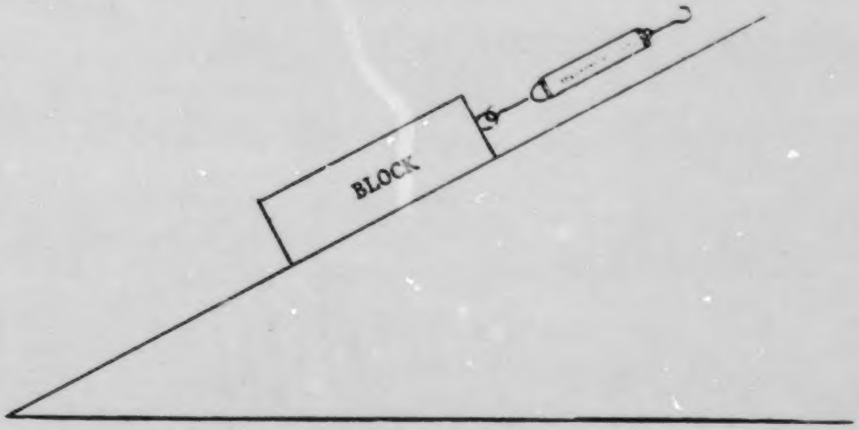

Figure 5

Name________________________

Section______________________

Expansion of the Idea

Part 3: Problems

1. Compare static and kinetic friction. Which is larger for any particular object? State a reason that you believe explains why one type of friction is greater than the other.

2. A block is resting on a horizontal surface. What could be done to make the force pressing the surfaces together not equal the block's weight? The surfaces must remain in contact. Explain why your plan would reduce the force pressing the surfaces together.

3. Describe how reducing the friction between your shoe sole and the floor would affect walking. What law of physics explains what you just described?

4. The coefficient of static friction between two pieces of steel is 0.74. How much force must be exerted to start a steel block weighing 98 newtons moving horizontally over a steel surface?

5. A 10 kg wooden block moves over a horizontal surface with an initial velocity of 4 m/sec. The coefficient of friction between the block and the surface is 0.4. How far will the block travel before stopping?

6. Explain why the coefficient of friction does not have units of measure.

7. The figure below shows a block of wood (A) on an incline. The block is attached to a rope which has been thrown over a pulley. The free hanging end of the rope is attached to a cement block (B). The friction between the rope and the pulley is negligible. The static coefficient of friction between the wood block and the inclined surface is 0.50 ($\mu_s=0.50$); the kinetic coefficient is 0.25 ($\mu_k=0.25$).

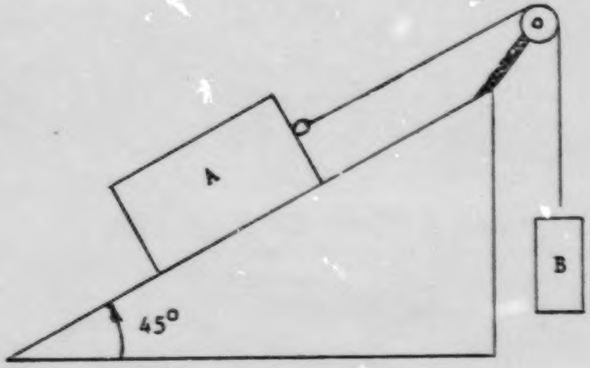

Figure 6

a. If block A has a mass of 100 kg, how much must block B weigh if both blocks A and B are to remain motionless?

b. How much extra weight must be applied to block B if block A is to move up the incline?

c. If block B were suddenly cut loose from the rope, with what acceleration would block A move down the incline?

Name________________________

Section________________________

Expansion of the Idea

Part 4: Reading Questions

1. Why must the normal force be equal to the weight of an object when the object rests on a horizontal surface?

2. Propose an hypothesis that would explain why rolling friction is less than sliding friction.

3. List the factor(s) on which friction depends.

4. List the factor(s) on which friction does not depend.

5. What must always be present before friction can occur? (Examples: rubbing your hands together, striking two pieces of flint together, shutting a warped door.) List some of the products of the friction resulting from these actions.

INVESTIGATION 10: FRICTION

READING: FRICTION, FRICTION, EVERYWHERE

Friction is a common, everyday occurrence. We deal with it in almost every aspect of our lives. We may even take it for granted. Erasure of our mistakes without friction would be difficult. So would be stopping our car or bicycle at a stop sign, paddling a boat across the lake, walking, keeping food on our fork, or lighting a match. Or...well, let's not get carried away with this. Friction is obviously important to us.

Of course, friction also has some nasty qualities. It eats our tires and wears out our brakes. It is responsible for those ear-piercing sounds chalk and fingernails make when run down the chalkboard. Friction makes doors squeak and makes us work harder. So, friction has its less desirable side, too.

What causes this phenomenon of delight and disaster? Let's examine a simple case of friction--erasing a pencil mark. What are the products of erasing an error from a piece of paper? First, and most important, the original marks have disappeared along with a thin layer of the paper. Then, there are the multitudinous eraser crumbs. Thus, the interaction between the eraser and the paper has worn away both the lettering and paper as well as part of the eraser. In addition, the paper and the eraser get hotter. Friction is caused by the interactions among the irregularities between two surfaces. Even smooth surfaces, such as glass, have microscopic irregularities. These bumps and valleys and tooth-like projections contact each other and actually rip off parts of the surfaces--as evidenced in our example of the eraser. Thus, brakes wear out; tires and erasers wear down.

What factors affect how much interaction exists between the surfaces of two objects? First, the force of friction is directly proportional to the force pressing the two surfaces together. This upward force of the surface on the object is called the normal force. It is equal to the weight of the object when the surface is horizontal and the object rests on the surface. (Use one of Newton's laws to explain this equality.) The result of this proportionality between friction and normal force is that the more an object weighs, the closer the surfaces are pressed together, and the greater the resulting force of friction between the surfaces.

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INVESTIGATION 10: FRICTION

Another factor which affects friction is the nature of the surfaces involved. You know from your experimentation that the force of friction between a painted block and a sheet of glass is less than that between an unpainted block and a table. The reason for this is that smooth surfaces have fewer irregularities than rough surfaces and, therefore, the tearing contact between them is less.

The force of friction also depends on the motion of the surfaces. You observed that the force required to initially move a block from rest was greater than the force necessary to keep the block moving. Two surfaces resting on one another *settle* and become closely associated. This allows the irregularities to weld together--to become interlocked. Thus, when one first attempts to pull a block across the table, these welds must be broken and the force of friction is great.

We call this friction between objects at rest *static friction*. (Static means *not moving*.) When the block is actually moving across the table, the surfaces have less opportunity to interact and the force of friction declines. We call this friction between moving objects *kinetic* friction. (Kinetic means *moving*.) Static friction, then, between two objects is greater than kinetic friction. (It is important to note that part of the force required to get the block moving is due to the force needed to overcome inertia.)

Suppose a ball of wood and a block of wood of equal weight had the same force exerted on them at the same instant. Which would you expect to stop first? If you guessed the block would stop first, you were right. The ball would continue to roll after the block had come to a rest. This indicates that rolling friction is less than sliding friction. What reason could you give for this? Perhaps you would guess that the ball has less surface area contacting the table at any point in time. However, your work with friction should have indicated that friction is independent of surface area if all the variables such as weight, material, etc., are controlled. The exact reason for rolling friction being less than sliding friction has not been determined at this time. Several hypotheses have been proposed. Try to formulate an hypothesis of your own for this difference between sliding friction and rolling friction.

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INVESTIGATION 10: FRICTION

How can the destructive actions of friction be controlled? Your laboratory experience should have indicated that placing a layer of oil between two surfaces reduces friction. Oil forms a thin film and, even though the layer is only a few molecules thick, will prevent the two surfaces from contacting one another. Graphite, a carbon substance, is also a good lubricant. The molecular nature of graphite is such that the graphite crystals actually slide over each other. The bonds holding the graphite crystals together are weak bonds. When graphite is placed between two surfaces, the adhesion between the graphite and the surfaces is greater than that between the graphite crystals themselves. The crystals are torn apart and slip over each other, thus surface interaction is reduced and friction is decreased. Ball bearings are used in the axles of wheels of roller skates, bicycles, and automobiles. Since rolling friction is less than sliding friction, bearings alleviate much of the wear that would occur in the wheel and the axle.

Oil, graphite, and bearings are good lubricants, but friction is still present in systems that employ them. An almost friction-free system can be developed by placing dry ice between two surfaces. Dry ice is solid (frozen) carbon dioxide. Carbon dioxide evaporates from a solid to a gas directly without going through a liquid phase. Thus, a film of gas forms between the two surfaces being separated and friction is reduced to almost zero.

We have seen that friction can be both helpful and destructive. As you begin to study machines in the following investigations, keep in mind the effects of friction.

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Name____________________

Section____________________

Introduction

Another word for the idea of balance is equilibrium. In this investigation, you are going to study all of the factors necessary to produce equilibrium in an object called the balance. You probably experimented with the balance when you were a child. It may have been called a see-saw or a teeter totter.

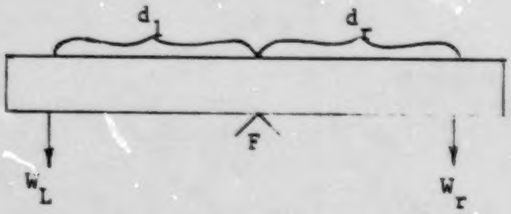

Figure 1

You are going to work with a balance which looks like the picture shown here. The bar is a meter stick which is mounted on the support labeled F in Figure 1. That support, F, is called the fulcrum. An especially designed pivot point holds the meter stick on the fulcrum. Your teacher will provide one and demonstrate how to use it. If you are unable to assemble the balance, ask your teacher to help you.

Exploration

After you have attached the pivot (often called a knife edge) to the meter stick, mount it on the fulcrum. Move the pivot around until you find that point on the meter stick which will allow it to naturally remain in a horizontal position. Do not be disturbed if the meter stick is not exactly horizontal. Just be sure that whenever you move one end of the meter stick vertically that it returns to its balanced position.

You have now found one point which allows the meter stick to balance naturally. Read that point on the stick and make a record of it in Table I. You will need it many times in this investigation. (Be sure to use the metric system for all measurements.) That point will probably be slightly different for every meter stick in the class. Check with your classmates to find out. Since each meter stick balances naturally at that particular point, it is called the natural balance point (NBP). Be sure you have found and made a record of the NBP for your stick. Leave the meter stick at its NBP throughout this entire investigation.

Figure 1 also shows two weights W_r and W_l, and two distances d_r and d_l. The subscripts r and l stand for right and left as you face the meter stick mounted on the fulcrum. You are asked to hang weights on the left and right sides of the meter stick. You may want to use weight holders to attach the weights to the meter stick. Ask your teacher about this. W_r and W_l should not be equal.

After you have attached W_r and W_l to the stick, move them around until the stick is balanced just as it was before you attached them. After the stick is balanced, find the distance each weight is from the fulcrum. Those distances are d_r and d_l. Record W_r, W_l, d_r, and d_l in Table I. Get two new weights, attach them to the meter stick and rebalance it. Continue that process until you have four sets of readings recorded in Table I.

Table I

Balance Point ______	W_r	d_r	W_l	d_l
1				
2				
3				
4				

The Idea

1. Study the data in Table I. What relationships can you see among W_r, W_l, d_r, and d_l? Write an equation that would describe that relationship.

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2. When a meter stick is placed at its natural balance point (NBP) on a fulcrum, how could a large weight balance a small weight?

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Name________________________

Section_______________________

Expansion of the Idea

Part 1: An Experiment

After your class has agreed upon what relationships exist among W_r, W_l, d_r, and d_l, use weights you have not used before and test those relationships. Design a table to record your data. Repeat with two different sets of weights. Be sure you understand the relationships among W_r, W_l, d_r, and d_l, because you will need them in the next experiment.

Name____________________

Section____________________

Expansion of the Idea

Part 2: A Problem and a Verification

You are going to use the weight hangers and meter stick you have been using in this part of the investigation. You are going to hang 270 gms 25 cm to the left of the fulcrum. Where must you hang 200 gms to balance the stick? Make your predictions and then check it with your apparatus.

Name______________________

Section____________________

Expansion of the Idea

Part 3: Reading Questions

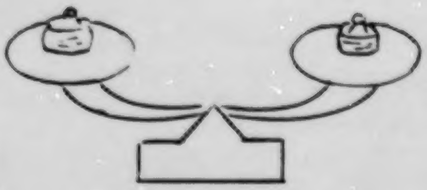


Figure 2

1. In the reading, the author assumed that the two pans of a double pan balance are of equal weight and distance from the fulcrum. Why was that a reasonable assumption?

2. Why would a double pan balance not function in an environment void of gravity?

3. Examine a single pan balance. What variables are manipulated to bring such a system into balance? (Hint: First determine the position of the fulcrum.)

INVESTIGATION 11: THE BALANCE

READING: WEIGHT OR MASS? A BALANCED VIEW

In Investigation 11, you examined the principles governing a simple balance upon which weights were hung. This is surely not the first balance you have encountered in your life. If you took chemistry, you often used a balance to weigh various chemicals you needed to perform your experiments. Wait a minute! Did you really *weigh* those chemicals? In other words, did you find their weight as you would if you had placed them on a bathroom scale? Let's examine this question more closely.

You know from your experience in Investigation 5 that weight is a measure of the force of gravity on an object. When you stand on the scales at the doctor's office, the scales are subject to gravity and, therefore, reflect your weight. That is, they measure your weight under the influence of the earth's gravitational force. If you took those same scales to the moon, they would measure your weight according to the moon's gravitational force. So, you would weigh about one-sixth of what you weighed on the earth. But then, you know all that.

Next, let's examine a typical double pan balance like the one you might use in chemistry or physics investigations. The fulcrum of such a balance is positioned between the two pans. We can assume that the two pans have identical weights and are equal distances from the fulcrum. Imagine that you place a small cart on one pan of the balance. (Or you might prefer to actually do this.) What happens to the other pan? Of course, it goes up. To bring the balance back into *equilibrium*, you have to place known *weights* on the empty pan. Once equilibrium has been achieved, you simply determine the amount you have added to bring the system into balance to find the weight of what you originally placed on the scales. But, have you really found the weight of the object?

Recall the equation you derived from your data in Investigation 11 for a balance system in equilibrium (i.e., $W_l d_l = W_r d_r$). Let's see how that equation applies to the double pan balance. First, the distance d_r is equal to the distance d_l. Also, the weight W_l is equal to the weight W_r. But, what is weight? You know from the data of Investigation 5 that weight is a product of mass and gravitational acceleration (that is, $W=ma$) so $mad=mad$.

INVESTIGATION 11: THE BALANCE

Just as a point for discussion, imagine that the object on the right pan is not being balanced by anything on the left pan such that $W_l d_l = w_r d_r$. You know, however, that $d_l = d_r$ and that the gravitational acceleration on each pan is the same. Thus, $d_l a_l = d_r a_r$. What is being measured by the balance? The equation, mad=mad, does not apply to this system out of equilibrium--not because the weights on the pans are different, but because the mass on each pan is different.

"Wait a minute!" you say. "If the masses are different, the weights are different, too." Of course, you are correct. Think through the problem one step further. Imagine your non-balanced system is taken to the moon. How much material would be required to bring the system into equilibrium compared to that amount necessary on the earth? Certainly the same weight would not be required since the a on the moon is only one sixth of that on the earth. But, the mass necessary would be the same as mass is independent of gravity.

Basically, what we are saying is that a double pan balance measures mass because the effect of gravity is the same on both pans and is, thus, cancelled out. That does not mean that a double pan balance is not affected by gravity. Surely such a system would not function in an environment void of gravitational forces.

INVESTIGATION 12: STUDYING THE NBP STUDENT GUIDE

Name ______________________

Section ______________________

Introduction

In Investigation 11, you found an equation that explained the relationship among W_r, W_l, d_r, and d_l on a first-class lever. That equation represents all the tools you have to work with on balance problems. So in this experiment, that equation represents your starting point when you are interpreting the data you will gather. Be sure you understand that equation before starting this investigation.

Exploration

Weigh the meter stick (call it W_s) and record its weight in Table 1. Move the fulcrum exactly 30 cms to the right or left of the meter stick's NBP just as shown in the diagram. Call that distance X. Now attach a weight (W) to the short end of the meter stick. Do not attach any weight to the longer end of the stick. Move the weight around until the stick balances. You have now found the distance d shown on the diagram. Record all the values on your balanced meter stick in Table I. Next move the fulcrum so it is exactly 20 cms from the NBP, balance the stick and again record the values in Table I. Repeat those actions with the fulcrum 10 cms from the NBP and two other values of your choice. Record all your data in Table I.

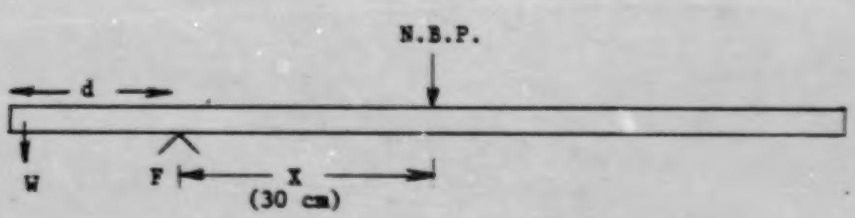


Figure 1

Table I

	W_s ( )	X ( )	W ( )	d ( )
1		30		
2		20		
3		10		
4				
5				

Summarize the data you have gathered.

The Idea

1. Using your understanding of the equation you developed in Investigation 11 ($W_l d_l = W_r d_r$), write an equation for the variables W, W_s, d, and X.

2. What do your data tell you about the weight of the stick and the NBP?

3. Why was the distance X always measured from the fulcrum (F) to the NBP?

Name________________________

Section______________________

Expansion of the Idea

Part 1: An Explanation and a Problem

Study the data shown in Table I. Determine how you can use the equation you developed in Experiment 11 to explain the data you collected in this experiment. Be sure you understand how to use the equation before going on to Investigation 13. After you have found out how to use the equation from Investigation 11 to explain data this investigation gave you, select a completely new point for the fulcrum, predict the distance (d) using your equation and then decide whether the equation you made correctly describes the relationship between the variables in the experiment.

Name________________________

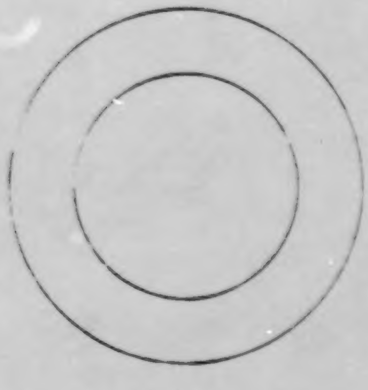
Section______________________

Expansion of the Idea

Part 2: Problem Set 2

1. A boy wants to sit on a see-saw (teeter totter) by himself. Explain how the see-saw would have to be set up. Also explain why your setup would enable the boy to make the see-saw work by himself.

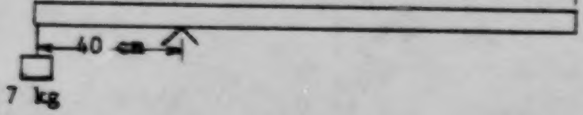
2.



Where is the center of gravity of the wheel shown in the diagram?

Figure 2

3.



The bar shown in the figure is of the same thickness over its entire length. How much does it weigh?

Figure 3

Name______________________

Section____________________

Expansion of the Idea

Part 3: Reading Questions

1. In the first reading, Archimedes is quoted as saying: "Give me a place to stand and I can move the world." How would he make use of the center of gravity to help him?

2. The second reading, Down and the Center of Gravity, lists several questions. Below are the questions underlined in the reading. Record answers to them.

   a. Which way is up?

   b. How would you define the center of an object?

   c. Write an operational definition of the center of an object using what you can observe about gravity.

d. What do all the data in the reading tell you about the point where the force of gravity acts on an object? Why do you think that point is called the center of gravity?

3. Figure 6 on page R12-14 gives you four figures and asks you to determine where they would balance. Draw those figures. Where do they balance?

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

READING: ARCHIMEDES--I CAN MOVE THE WORLD*

One man, it might be said, once fought an army. Ancient historians tell us that the man was old, over seventy. The army was that of the strongest power in the world--Rome itself.

But the old man, a Greek, fought the Roman army to a standstill for nearly three years--and almost won. The old man was Archimedes of Syracuse, the greatest scientist of the ancient world.

The Roman army knew his reputation well and he lived up to it fully. Legend says that when curved mirrors were set up on the walls of Syracuse, a Greek city in Sicily, the beseiging Roman ships caught on fire. It wasn't sorcery; it was Archimedes. When huge claws were extended outward on beams, ships were caught, raised, and overturned. It wasn't magic; it was Archimedes.

It is said that when the besieging Romans caught a glimpse of rope or wood being raised above the walls of Syracuse, they hoisted sail and ran.

For Archimedes was different from the Greek scientists and mathematicians who had preceded him, great as they were. Archimedes went beyond them in imagination.

For instance, to work out the areas enclosed by certain curves, he adapted existing methods of computation and came up with a system that resembled integral calculus. This was nearly two thousand years before Isaac Newton devised modern calculus. Suppose Archimedes had Arabic numerals to work with instead of the clumsy Greek numbers. He might have beaten Newton to the punch by 2,000 years.

Archimedes went beyond his predecessors in daring. He denied that the sands of the sea were too many to be counted. So he devised a method to count them. Not only them, but the grains of sand it would take to cover the earth. Not only that, but the grains of sand it would take to fill the universe. In doing this, he invented a new way of expressing large numbers. Our modern methods are similar in some ways to the one he devised.

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

Most important, Archimedes did what no man before him had done. He applied science to the problems of practical, everyday life. The great Greek mathematicians before Archimedes--Thales, Pythagoras, Eudoxus, Euclid--all considered mathematics to be abstract. It was a way of studying the majestic order of the universe--nothing more. It had no practical applications. They were intellectual snobs who despised practical applications. They considered such things fit only for merchants and slaves. Archimedes shared this snobbery to a great extent, but he was willing to apply his knowledge of mathematics to practical problems.

Archimedes was born at Syracuse, Sicily. The exact year of his birth is in doubt, but it is believed to have been 287 B.C. At that time, Sicily was a Greek land. Archimedes was the son of an astronomer and related to Hiero II, King of Syracuse from 270 to 216 B.C. He studied at Alexandria, Egypt, the intellectual center of the Mediterranean world, then returned to Syracuse and immortality.

He had been taught at Alexandria that a scientist was above practical affairs and everyday problems. At the same time, these everyday problems fascinated Archimedes. He could not keep his mind off them. He was ashamed of this interest and refused to keep any records of his mechanical devices. But, he kept on making the devices. Today, his fame rests upon them.

Long before the Roman ships sailed into the harbor at Syracuse and the Roman army set up its siege, Archimedes had become renowned.

One of Archimedes' early achievements was setting up the abstract theory that explains the basic mechanics of the lever. Imagine a shaft balanced on a pivot with the length of the shaft on one side of the pivot ten times the length on the other. Pushing down the shaft at the long end moved the short end up only one-tenth the distance. However, the force pushing the long end down was multiplied ten times in the push of the short end up. In a way, distance was being exchanged for force.

Using his theory, Archimedes saw no limit to this exchange. A man had only a limited amount of force at his disposal, but distance was unlimited. Therefore, make the lever long enough, push the long end down far enough, and any weight could be lifted at the short end.

Archimedes said "Give me a place to stand, and I can move the world."

King Hiero called what he thought was a bluff. He demanded that Archimedes move something heavy. Not the world, perhaps, but something heavy. So Archimedes chose a ship at the dock and had it loaded with freight and passengers. Even when empty, it could not have been dragged out of the dock and into the sea without many men pulling at many ropes.

But Archimedes tied the ropes together and arranged a pulley device (a kind of lever, using ropes to take the place of the shafts). He then pulled at the rope. Singlehanded, he drew the ship slowly into the sea.

Hiero was now quite content to believe that his great kinsman could move the earth if he wanted to. He had enough faith in him to set him seemingly impossible problems.

A goldsmith had made a gold crown for Hiero. The king wondered whether the smith had been honest. He might have kept some of the gold given him and substituted silver or copper. So Hiero ordered Archimedes to determine whether the crown was pure gold--without damaging the crown.

Archimedes was puzzled. Copper and silver were lighter than gold. If they had been added to the crown, they would take up more space than would an equal weight of gold. If he knew the space taken up by the crown (that is, its volume) he could give Hiero the answer. But how was he to determine the volume of the crown without beating it into a solid mass.

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

Archimedes took his problem to the public baths. Probably he sighed wearily as he lowered himself into a full tub and watched the water overflow. And then, he sat up thunderstruck. For it suddenly occurred to him that his body was pushing water out of the tub. The volume of water pushed out must be equal to the volume of his body pushing in. To find the volume of anything, you merely measured the volume of the water it displaced.

He had discovered the principle of displacement in one flash of intuition! From this, he deduced the laws of buoyancy and specific gravity.

Archimedes could not wait. He sprang out of the bath and ran home through the street, naked, and dripping wet. As he ran, he cried over and over again, "I have it. I have it." He cried it in Greek, of course, "Eureka! Eureka!" and the word is still used today to announce a glad discovery.

He filled a vessel with water, placed the crown in, and measured the volume of the water displaced. Then he did the same thing with an equal weight of pure gold. The volume of water displaced was smaller. The gold in the crown had been mixed with a lighter metal, giving it greater bulk (volume) and causing more water to overflow. The king ordered the smith executed.

Even in his old age, Archimedes could not resist the challenge of a problem. In 218 B.C., Carthage (in North Africa) and Rome went to war with each other, and the Carthaginian general, Hannibal, invaded Italy. He seemed on the verge of destroying Rome. While King Hiero lived, he kept Syracuse neutral, though in a dangerous position between two fighting giants.

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

After King Hiero's death, however, a group that favored Carthage came into power. In 213 B.C., Rome laid siege to the city.

For three years, the aged Archimedes held off the Roman army. But one man could do only so much. At last, in 211 B.C., the city fell. But even defeat could not affect the restless brain of Archimedes. As the soldiers swarmed into the city, he was working out a problem from a diagram. A soldier ordered him to surrender, but Archimedes paid no attention. The problem was more important to him than a little thing like the sack of a city. Archimedes said, "Don't disturb my circles."

So the soldier killed him.

The achievements of Archimedes have become part of mankind's heritage. He showed that it was possible to apply a scientific mind to the problems of everyday life. He showed that an abstract theory in pure science--the principle that explains the lever--could save the straining muscles of man.

He showed the reverse, too. By beginning with a practical problem--that of the possible adulteration of gold--he discovered a scientific principle.

Today, we believe that the great duty of science is not only to understand the universe, but also to better the lot of mankind in every corner of the earth.

* Isaac Asimov, Breakthrough in Science, (Scholastic Book Services: New York, 1959) pp. 9-14.

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

READING: DOWN AND THE CENTER OF GRAVITY*

Which way is down? When you release an object above the surface of the earth, it moves toward that surface. If someone asks you why the object does so, you would probably say, "Because of gravity." Further, if you were asked to name the direction in which objects move under the influence of gravity, you would probably answer "down." But which way is down?

You now have a distinct question to answer or a problem to solve. Which way is down? Think for a moment and see if you can give an operational definition of down. Saying, "Well, it's that way," and pointing are not good enough. To solve this problem properly, you have to make observations, take measurements, or do experiments; that is, do what a physicist might do. You will arrive at the solution to the problem only after you think about, or interpret, these observations, measurements, and experiments.

To help yourself gather data to solve the problem, you can do a pencil and paper experiment. With a compass, draw a circle about seven inches in diameter on a sheet of paper and clearly mark its center. Use your ruler and draw several lines tangent to this circle. Next erect a perpendicular line at the point of tangency, the point between each tangent line and the circle. Be sure the lines are really perpendicular to the tangents. Figure 1 shows two sets of tangent and perpendicular lines such as you have drawn. You should draw more than two sets. Label the circle earth and sit back and look at it.

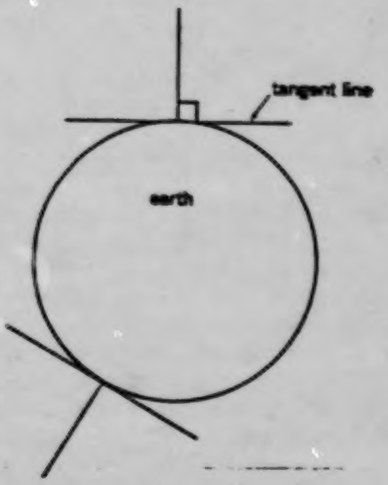


Figure 1. A line tangent to a circle touches the circle at only one point. Two lines are perpendicular when the angle between them is 90°. After drawing several sets of tangent and perpendicular lines, can you state which way is down? Is your statement an operational one?

Figure 1

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

Now obtain a world globe, a basketball, or some other spherical object. Locate a continent on the globe, or imagine one if you are using an unmarked sphere. Using two straight objects, such as two pencils, place a tangent and a perpendicular to that on the globe. What does the perpendicular pencil represent to the continent upon which it is standing? Before continuing with the pencil and paper experiment be sure you understand the relationship between the tangent line and the line perpendicular to the tangent line.

Have you figured out that the perpendicular lines you just drew can represent objects, including people, at different points on the earth's surface? Now, imagine yourself standing at each of these spots on the earth and pointing in the direction of down. You would, of course, point to a spot below your feet.

Once more use your ruler and extend the perpendicular lines you just constructed into the interior of the circle. What happens to the lines? The data from your pencil and paper experiment tell you an important fact. Regardless of where you are on the surface of the earth, the direction you call down is always the same. How would you describe that direction? Realizing how you determined the direction down is as important as knowing what that direction really is.

You were presented with a problem that resulted from your observation that objects fall down. You may or may not have been able to give an immediate answer to the problem. If you answered it before doing the pencil and paper experiment, you were probably not quite sure whether or not your answer was right. The reason for this is that your immediate answer was probably a guess, and was therefore not based on an experimental procedure or operation. To solve the problem and to obtain data, you needed to do an experiment, in this case a pencil and paper experiment.

Perhaps you have thought of an experiment as a procedure that is long and complicated, and indeed, it might be. Your experiment, however, was not long or complicated. It was based on your knowledge that the earth is a sphere and that objects standing on the surface of the earth are perpendicular to this surface. With this knowledge, you were able to use simple procedures to carry out the experiment. Simple though it was, you used the experiment to solve the problem. An experiment, then, can be described as something that is done to provide data to solve a clearly defined problem. The simple procedures you used allowed you to discover what direction is down.

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

There is another term that may be troublesome to define. That term is up. Carefully consider in what direction you would point if someone were to ask you Which way is up? Return to the diagram of the earth you constructed when you were defining down, and add any additional lines you need to form a definition of up.

What part of an object falls along the down line? In Figure 2, you see that a freely-falling metal sphere follows a path parallel to the freely-hanging plumb bob. The suspended plumb bob is perpendicular to the earth's surface and you know that such a perpendicular is directed toward the earth's center. No matter how many times you repeat this experiment, you will always find that objects fall toward the earth along a line than can be extended to the earth's center. On the basis of these data, you may conclude that falling objects move toward the center of the earth. You also know that it is gravity that causes objects to fall toward the earth. On the basis of the last two sentences, what generalization can you make?

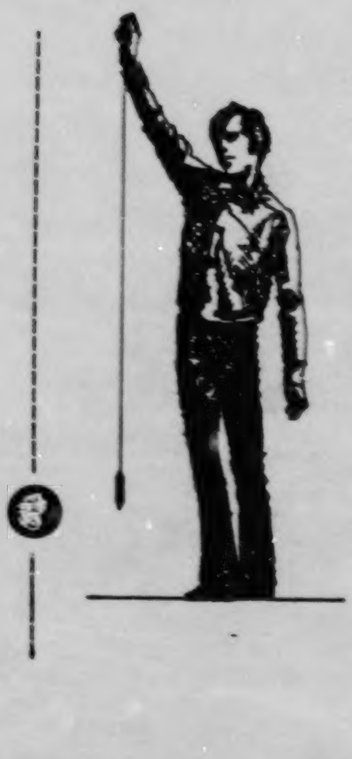


Figure 2. All objects fall along a line perpendicular to the earth's surface.

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

Suppose that a large, irregularly-shaped object like the huge boulder shown in Figure 3 is falling toward the earth's center. You know that the spot known as the center of the earth is a point deep within the earth's interior. In Figure 3, the huge boulder moves in a straight line toward a point. You know that several different points scattered about on the boulder shown in the figure cannot all move at the same time toward the same point along one straight line. You have learned that at any point on the earth's surface the direction between that point and the center of the earth is a straight line.

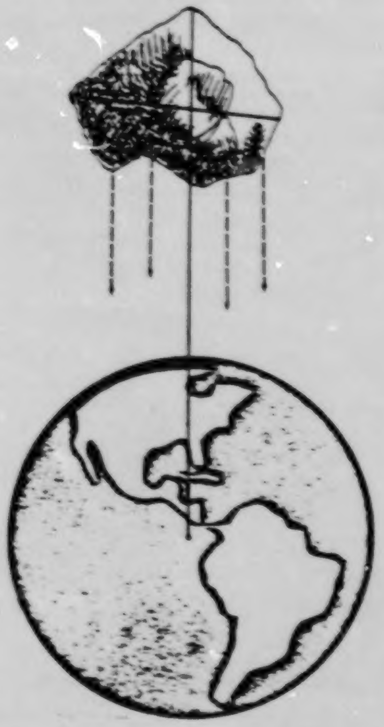


Figure 3. What point in an object moves toward the earth's center?

You know that down is represented by one single straight line toward the earth's center and that this line is the path followed by falling objects. You also know that when a huge object falls toward the earth, all the individual points in it cannot possibly follow that single straight line. So you are faced with what seems to be a contradiction. Here again you have a problem that you may need data to solve.

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

The first thing you need to do to solve the problem is to make an exact statement of what the problem is. It is very hard to solve a problem that is not precisely worded. Before reading on, go back over the last paragraphs and decide what the problem is, then write down the problem in the form of a question. Once you have in mind exactly what you want to investigate, you can begin to collect data.

To get the data you need, once again do a pencil and paper experiment. Draw a circle with a diameter of six inches in the center of a sheet of paper. Label the circle EARTH. Next, draw several smaller circles that are externally tangent to the large circle representing the earth. In order to get good results from this experiment, your circles must be perfectly circular. The size of the circle is not nearly as important as making it perfectly circular. Using the points of tangency, between the small circles and the six inch circle as beginning points, draw lines that will indicate a downward direction on the earth, as in Figure 4. From the points of tangency between each of the circles and the large circle, extend the down lines outward into the small circles. What do you find?

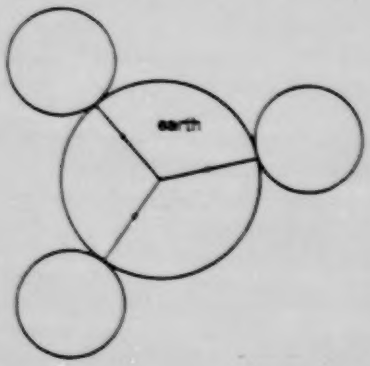


Figure 4. Two circles are tangent if their circumferences have one point in common. How does this diagram help you explain what part of an object moves toward the center of the earth?

Imagine that the circles you just drew in the pencil and paper experiment were really spheres and that the spheres were dropped from a height above the earth. They would move toward the earth under the influence of gravity. When they eventually touched the earth, as the circles did in the experiment, a down line extended from the center of the earth through their points of tangency would also go through the centers of the spheres. You found in your pencil and paper experiment, that when the down lines were extended, they went through the center of the circles. Thus, for all sizes of spherical objects there is one point, the exact center of the sphere, that moves toward the center of the earth. All other points in the sphere would move along lines that were parallel to the down line and which, when extended, would miss the center of the earth.

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

Again let's ask, "What part of an object falls along the down line?" You can now answer that if the object is a sphere, the center of the sphere falls along the down line. But the original problem was, "What point of any object falls along the down line?" To solve the problem, you have started by doing what a physicist often does--making a simplifying assumption. Instead of trying to solve the problem of any oddly-shaped object, you have solved it for the simple case of a sphere. After you have solved the simplified case, you can remove some of the simplifying assumptions and solve a more complex case that is truer to life. Said another way, if you have a problem, modify it to a problem you can solve, then go back to see if the solution will help with the original problem.

So now, what about nonspherical objects? Repeat the pencil and paper experiment you just did and this time use squares and rectangles. Remember, that for spheres the exact geometric center moves toward the center of the earth. These are good data from which to hypothesize. The data you gathered from the problem involving the spheres showed you that the center of a sphere under the influence of gravity moves toward the center of the earth. Now you have no reason to believe that squares and rectangles--and their three-dimensional equivalents--will behave any differently. (Or do you?) So let's hypothesize that the geometric centers of these objects will also move toward the center of the earth.

This hypothesis is based on a definite interpretation of data. Do not confuse such an hypothesis with a guess; a guess is what you believe will happen because of what you feel and not what you know. There is nothing wrong with a guess! Many scientific discoveries have been made because of hunches that have been followed or guesses that have been made. But, when making a statement that you want to call a hypothesis, you should have a reason for doing so. So, if you start with a guess, try to hunt around until you find some supporting evidence that will let you turn your guess into a hypothesis based on data. Of course, while you are hunting for supporting facts, you may find some that disprove your guess.

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

Can you apply the hypothesis that the center of a falling object will move toward the earth's center to any object? How would you define the center of an object? For the experiments you did, it was easy to define the centers of the circles, squares, and rectangles by using geometry. These are all symmetrical figures. Spheres, cubes, and rectangular boxes are also symmetrical in three dimensions. How would you define the center of the object shown in Figure 5? For the moment, you must restrict your hypothesis and say that when symmetrical objects fall under the influence of gravity, the centers of such objects move toward the center of the earth.

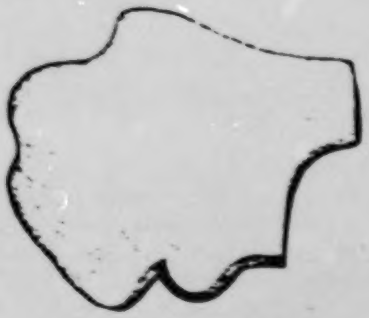


Figure 5. How would you define the center of this object? What point in this object would fall along the down line?

Here is the process of investigation so far. A problem has led you to gather facts in order to make a hypothesis. The next step should be to test the hypothesis to see if it has a broader application. You have seen the place of simplifying assumptions in the process and how they restrict any hypothesis you make based upon simplifying assumptions.

Right now, your hypothesis about what part of an object falls along the down line is restricted to symmetrical objects. It would be nice to somehow remove the restriction. To do so, you must answer another question, "How do you define the center of an object that is influenced by gravity?" What means, other than geometry, can be used to define such a center? Write an operational definition of the center of an object using what you can observe about gravity.

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

What does gravity do? Gravity cannot be seen or heard. So, if you are to learn what it is, you must study what it does. That is, you must study the effect it has on objects you can see and measure. What effect of gravity can you observe? What effect of gravity have you been observing all along as you worked your way through this chapter?

Lay your pencil in the desk and flick it with your finger. What do you observe? If you had not pushed your pencil, would it have moved? Use your finger to pull your pencil toward you. Both the push and the pull of your finger set the pencil in motion. A push or a pull is called a force. Whenever a force is applied to an object, the object moves; unless, of course, there is some other force being applied to keep it from moving. Look at the situation the other way around. If something is set in motion, a force must have been applied to start it moving.

Hold your pencil an inch above the desk. Now release it. There was motion by the pencil; therefore, a force must have been applied to it. At the beginning of the chapter, you saw that the reason given for the motion of a falling object toward the earth was gravity. The effect of gravity on an object released above the earth's surface is motion. Therefore, an object under the influence of gravity experiences a force. This force is called the force due to gravity or the gravitational force and is considered to be a force of attraction only and will be so considered until somebody observes gravitational repulsion.

Now you can answer the question, "What does gravity do?" The answer is that gravity attracts with a force--the force due to gravity. So here is another observation about gravity that may be of some use to you in your continuing investigation of how objects fall.

Irregularly-shaped objects and the down line. Earlier in the chapter, you found evidence to show that the center of a symmetrical object was attracted toward the center of the earth. You have not yet been able to state a hypothesis about what part of an irregularly-shaped object is attracted to the center of the earth. You cannot use the paper and pencil experiment technique here because there are all manner of irregularly-shaped objects that you could draw. Working with any one of them would not allow you to generalize from your drawings to all objects. There is, however, another simple investigative procedure you can use, based on your knowledge of the attractive force of gravity.

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

Obtain three or four different very flat, nonsymmetrical objects. The objects you see in Figures 5 and 6 may give you some ideas. Lay these objects on a horizontal, flat surface and ask yourself, "How can I balance each of these objects by using a single point of support?" As a support, for instance, you could use the point of your pencil. You could also use the flat top of the eraser on the pencil for your point. After a little experimentation, you will find that an irregularly-shaped object can almost always be balanced at one point.

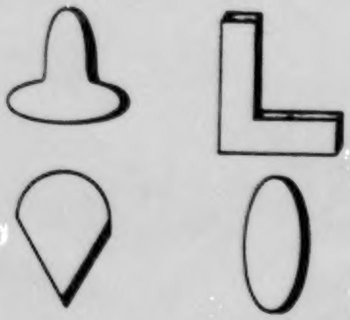


Figure 6. Where do these objects balance?

Now take a few regularly-shaped flat objects and find the point where you can balance them. Use a circle, a square, or a rectangle, for example. Combine what you know about balancing irregularly-shaped objects with what you just found out about balancing regularly-shaped objects. Add to the foregoing the fact that the geometric center of a sphere, a symmetrical object, moves toward the center of the earth. What do all these data tell you about the point where the force of gravity acts on an object? The name given that point is the center of gravity. Why do you think it is so named?

What did you do when you balanced the flat objects? You pushed on the flat objects while the force of gravity pulled on them. You exerted a force to counteract the force of gravity. The center of gravity of an object is defined by how and where you exert a force on the object. Now, write down an operational definition of the center of gravity of a flat object. For symmetrical objects, you may find the center of gravity by geometry. For irregularly-shaped objects, however, you need to do an operation to find the center of gravity.

INVESTIGATION 12: STUDYING THE NATURAL BALANCE POINT

The flat objects whose centers of gravity you found were not entirely two-dimensional--they had some thickness. How would you go about finding the center of gravity of an irregularly-shaped object like the one shown in Figure 7? How would you find the center of gravity of the boulder shown in Figure 3? Write down an operational definition for the center of gravity of a three-dimensional object.

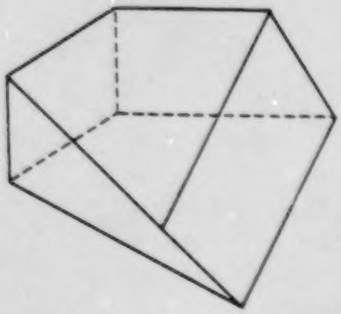


Figure 7. How do you find the center of gravity of three-dimensional, irregularly-shaped object?

One final thing before going on to investigate some other effects of gravity. Write down the answer to this question, "What part of an object falls along the down line?"

* John W. Renner and Harry B. Packard, Investigation in Physics, (Lyon and Carnahan: Chicago, 1974) pp. 26-32.

Name______________________

Section______________________

Introduction

The ideas from Investigations 11 and 12 will be used in this investigation. You are asked to state those ideas in writing below before doing this investigation. If you do not remember what those ideas are, go back to Investigations 11 and 12 and refresh your memory. You may also need to discuss those ideas with other students and your teacher.

Idea from Investigation 11

____

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Idea from Investigation 12

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Exploration

Find the NBP of the meter stick, weigh it, and make a record of that value. You will need it later in this experiment. Keep the stick at its NBP and balance it using the following weight combinations.

Combination 1:

Two weights at different distances from the fulcrum on the right of the fulcrum, and one weight on the left side of the fulcrum.

Combination 2:

Two weights at different distances from the fulcrum on the left of the fulcrum, and one weight on the right side of the fulcrum.

Combination 3:

Two different weights at different distances from the fulcrum on each side of the fulcrum.

NOTE: When an X appears in a cell of the table, nothing is to be written in that cell.

Table I

	Left side of fulcrum				Right side of fulcrum			
Weight Combination	W	d	W	d	W	d	W	d
1			x	x				
2							x	x
3								

Study the data in Table I. An equation can be written that explains why the meter stick balances with all three combinations of weights. Write that equation here.

You need to test the equation you just wrote. To do that use weight combinations 4, 5, and 6 shown below. But before putting the last weight on the stick, use your equation to predict where it should be placed. Add the weight at that point and balance the stick. How do the predicted d and measured d compare? Record your data in Table II.

Combination 4:

Three weights at different points on the left of the fulcrum and two weights at different points on the right of the fulcrum.

Combination 5:

Three weights at different points on the right of the fulcrum and two weights at different points on the left of the fulcrum.

Combination 6:

Three weights at different distances on each side of the fulcrum.

Table II

	W_r=	d_r=	W_l=	d_l=
Combination	W_r=	d_r=	W_l=	d_l=
4			W_l=	Predicted d=
				Measured d=
	W_r=	d_r=	W_l=	d_l=
Combination	W_r=	d_r=	W_l=	Predicted d=
5				Measured d=
	Wr=	dr=		
	W_r=	d_r=	W_l=	d_l=
Combination	W_r=	d_r=	W_l=	d_l=
6	W_r=	d_r=	W_l=	Predicted d=
				Measured d=

Study the data in Tables I and II. An equation can be written that explains why the meter stick balances with all combinations of weights. Write that equation here.

The Idea

You have been experimenting with an important idea in physics known as torque. You, your teacher, and the other students need to make a statement about the law of torque that your investigation has shown you. Write that law here.

Name________________________

Section______________________

Expansion of the Idea

Part 1: An Experiment

The law of torque you just invented needs to be tested. The following weight combinations will enable you to do that. Move the fulcrum on your balance to a point exactly 30 cms to the left of the NBP. Balance the stick using these combinations. Do not place a weight at the stick's NBP. Record your data in Table III.

Combination 1:

One weight on each side of the fulcrum.

Combination 2:

Two weights on the left of the fulcrum and one weight on the right of the fulcrum.

Name____________________

Section____________________

Combination 3:

Two weights on the right of the fulcrum and one weight on the left of the fulcrum.

Table III

Weight of the stick=____________________

NBP____________________centimeter point

Combination	Right side of fulcrum	Left side of fulcrum
1	$W_r=$ $d_r=$	$W_l=$ $d_l=$
2	$W_r=$ $d_r=$	$W_l=$ $d_l=$ $W_l=$ $d_l=$
3	$W_r=$ $d_r=$ $W_r=$ $d_r=$	$W_l=$ $d_l=$

Name________________________

Section_____________________

Expansion of the Idea

Part 2. A Prediction

Study the data in Table III. Use the equations you developed from the data in Table II and test the law of torque with the data from Table III. Show your work below.

Secure two weights you have not used before. Leave the fulcrum of the balance at the 30 cm mark. Hang one weight to the left of the fulcrum. Be sure the balance is unbalanced. Use the equation for the law of torque you have developed and predict where a weight on the right should be placed. Show the computation you did to make your prediction in the space below.

Name________________________

Section______________________

Expansion of the Idea

Part 3: Problems

1. There is a long plank resting on the edge of a cliff. A 5.0×10^2 kg mass is sitting on the plank 3.0 m from the edge of the cliff. How far can a man, whose weight is 833.0 N, walk out on the plank before it starts to tip? (Assume that the plank has no mass.)

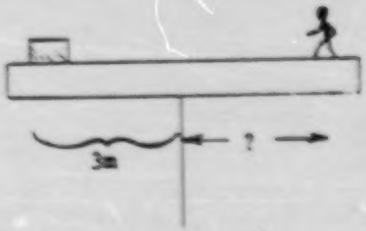


Figure 1

2. Suppose the problem is the same as in Figure 1 except that the plank has a weight of 110.0 N and is 25.0 m long. It is uniform and 4.0 m of it are resting on the side of the cliff. How far can the man walk now?

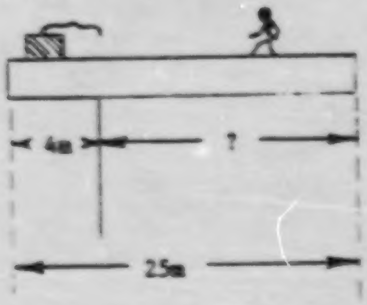


Figure 2

3. Mark and Carl carry a sack weighing 6.0×10^2 N on a pole between them. If the pole is 2.0 m long and the load is 0.50 m from Carl, what force does each exert? (Neglect the weight of the pole.)

4. The center of gravity (NBP) of a pole which is thicker at one end than at the other is located 10 feet from its thicker end. The weight of the pole is 400 pounds. The pole is 40 feet long and supported at the middle. How much force must be supplied at the small end of the pole to balance it?

5. A 100 pound, uniform beam 14 feet long is being carried by two men. One man, A, supports the beam two feet from the left end and the other man, B, supports the beam three feet from the right end. An 80 pound load is now placed on the beam. Where must it be placed so man A will support twice as much weight as man B?

Name__________________________

Section________________________

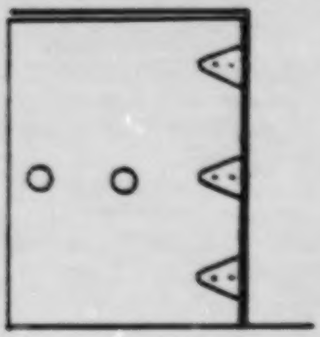
Expansion of the Idea

Part 4: Reading Question

Why is it preferable to label a balanced system as an equilibrium between clockwise and counterclockwise torques rather than between left and right torques? Specifically, why is the equation $T_l = T_r$ true for all balanced systems?

INVESTIGATION 13: MULTIPLE FORCES

READING: TORQUE AROUND YOU



You are given the task of installing a heavy door. You attach it to the wall with three sturdy hinges and long, strong wood screws that sink far into the wall. You know now that when the door opens, it turns around the place on the wall where it is attached. You also know that to open the door you have to exert a force on it.

Most doors have the knob attached at the edge opposite the hinges. When you open a door, you pull on the door toward yourself. In other words, the force is exerted perpendicular to the door. The door turns about the wall to which it is attached. So the distance from the point of rotation to the point of application of the force is the distance from the wall to the door knob. Opening the door requires a torque.

In some newer homes, the knob is sometimes placed near the middle of the door. While that placement of the knob may be pleasing to the eye, it cuts down on the distance through which the force can act. The force exerted, therefore, must increase to open a door. Suppose the door knob were placed exactly in the middle of the door. That would mean that the arm for the torque is only one-half what it would be if the knob were on the edge. A certain torque is necessary to open the door. Therefore, twice as much force must be exerted on the middle of the door as would be needed if the knob were on the door's edge.

Notice that a torque always produces a rotation. When the door opens, it turns, or rotates. Of extreme importance is the idea that the object rotating turns about (or around) a particular point. The door turns about the wall where the hinges are connected. In Investigation 13, the meter stick was balanced on the fulcrum. The weight on one side of the meter stick attempted to rotate the stick about the fulcrum in one direction. The weight on the other side of the meter stick attempted to rotate the stick in the opposite direction. When the stick was balanced, the torque in one direction balanced the torque in the other direction. The net torque acting on the stick was zero. That can be written as ΣTorques=0.

INVESTIGATION 13: MULTIPLE FORCES

But all of the torques on the meter stick were real torques. If their sum is zero, some have to be labeled positive and some negative. Whenever a torque tries to rotate an object in a clockwise (CW) direction, it is a positive torque. Torques that attempt to rotate an object in a counterclockwise (CCW) direction--opposite to the direction of the motion of a clock--are called negative torques.

So torque has a direction that carries an algebraic sign. When an object balances, all the torques on one side of the object balance all the torques on the other side. Said another way, the CW torques balance the CCW torques. Or CW Torque-CCW Torque=0.

The pistons in an automobile are connected to the crankshaft by connecting rods. The rods are at right angles to the crankshaft. When the gases in the cylinder explode, they exert a force on the piston which pushes the connecting rod. So the force from burning fuel results in a torque. The crankshaft changes the up and down (linear) motion of the piston and rods into rotational motion.

Torque produces rotation. Whenever a force operates at an angle to a distance which is connected to a point of rotation, torque exists. The distance--sometimes called the lever arm or movement arm--rotates about a particular point. Torque always produces rotational motion.

INVESTIGATION 14: THE LEVER

STUDENT GUIDE

Name________________________

Section______________________

Introduction

In Investigation 11, you placed a meter stick at its NBP and balanced it by placing weights on both sides of the fulcrum. When the meter stick was balanced, the products of the weight and distance from the fulcrum on each side of the NBP were equal. That is, $W_r d_r = w_1 d_1$.

You know what weight is a force. So the apparatus you worked with in Investigation 11 has the fulcrum placed between two forces. Such an apparatus--or machine--is a first class lever, and you are going to use it in this experiment.

Exploration

Balance the meter stick at its NBP. Place one kilogram of weight ten centimeters from the end of the meter stick opposite to the end where the screw eye is found. (Record all your data in Table I.) Hook the spring balance into the screw eye in a manner that permits reading it conveniently. Pull down on the spring balance and lift the weight on the stick's opposite end. Measure the distance the weight moves up and the distance the spring scale moves down. What decision must you make before those measurements can be made?

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____

Practice with the apparatus until those measurements can be made easily before you record any data. Move the one-kilogram weight to two different heights. Now attach the weight to a second point on the side of the meter stick opposite the spring scale. Take two readings of the height, the weight, and spring scale moved at each of those points. Increase the weight to 1.5 Kgms and repeat taking the measurements just taken. Record your data in Table I.

Table I

		First Readings			Second Readings		
Points Weight is Attached	Weight Lifted	Distance Weight Moved	Distance Scale Moved	Scale Reading	Distance Weight Moved	Distance Scale Moved	Scale Reading
10 cms	1 kg						
-- cms	1 kg						
10 cms	1.5 kg						
-- cms	1.5 kg						

The Idea

Study the data in Table I. Keep in mind you have four variables you are working with. Those variables are the weight being lifted, the force necessary to do the lifting, and the distance the weight and the force move while being lifted. What evidence can you give that proves those variables are related? Remember there is only a limited number of operations you can do with numbers. You are, therefore, looking for a mathematical relationship among those numbers.

Name______________________

Section______________________

Expansion of the Idea

Part 1: An Experiment

You have now invented a relationship that explains which numbers in Table I are related and how they are related. Use several different weights, each placed at several different points and test that relationship. Design a table that can be used to record your data. Draw your table in the space which follows and record your data in it. Label it Table II. Following the table, demonstrate how the mathematical relationship you found works.

Name________________________

Section________________________

Expansion of the Idea

Part 2: Problems

1. How much work is done in raising a 100 N weight 20 m into the air?

2. A 2 kg body has its velocity changed from 9 m/sec to 11 m/sec in 100 m over a period of 10 seconds. How much work is done on it?

3. A plane weighing 196,000 N starts from rest and reaches a velocity of 100 m/sec by the time it has travelled 5,000 m down the runway. How much work has it done?

4. A boy pulls a loaded sled by means of a rope which makes an angle of 45.0° with the horizontal. The force on the rope is 20 N. How much work is done in pulling the sled along a level road for a distance of 1.000 km?

5. How much work must you do in climbing 24 steps if each step is 15 cm high?

INVESTIGATION 14: THE LEVER STUDENT GUIDE

Name____________________

Section__________________

Expansion of the Idea

Part 3: Reading Questions

1. Explain why pushing on a moving object at right angles (sideways) does not do work on the object.

2. Compare work and torque. How are they similar? How are they different?

INVESTIGATION 14: THE LEVER

READING: WORK AND ENERGY MEASUREMENT*

All schemes of raising loads, or stretching springs, or propelling carts on rough roads require a force that moves along. We haul a load upwards, along the line of its motion; we pull the end of the spring outward along the line of its stretch. How can we make a general scheme of fuel billing for such jobs, energy measurement as we shall call it?

Consider the fuel demand for raising loads in building and mining, the oldest mechanical examples of a clear need for fuel. Suppose we wish to raise a two pound load three feet vertically. Start with a one pound load and raise it just one foot. That will cost some fuel. Common sense tells us that if it costs so much fuel to raise the one pound load one foot, it will cost the same for the next foot, and the same for the next, etc. Raising it three feet altogether will cost three lots of one foot raising fuel.

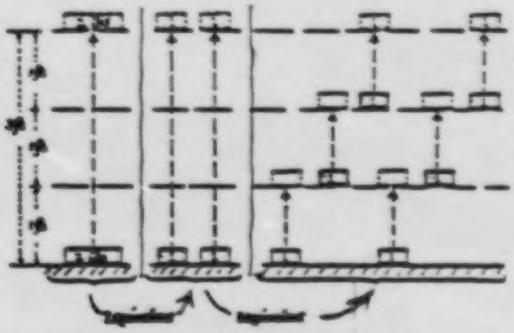

Figure 1. Splitting Weight-Raising Job up into Stages

Now change to the larger load, two pounds. Raising a double load is like raising two single loads separately. Common sense and direct experiment tell us that the fuel requirements are additive: the raising job can be broken up into separate stages. Then, to find the cost of raising two pounds three feet, we split the job into two sub-jobs of raising one pound three feet and subdivide each sub-job into three unit-jobs of raising one pound one foot. Then we say, raising two pounds three feet will cost twice as raising one pound, and three times as much as for one foot, so it will cost 2x3 or or six times as much as raising one pound one foot. It will cost six foot·pounds. A foot·pounds means:

1 foot Distance·1 pound-weight Force.

INVESTIGATION 14: THE LEVER

We might picture the total job being done by a crew of identical demons, each raising one pound to a shelf one foot higher--another demon taking over from there up to the next shelf--and each repaid by a standard grain of food. Common sense suggests that this splitting-up into unit jobs is allowable: that fuel consumptions are additive. Only experimental tests could justify this treatment completely for all varieties of load raising. They do.

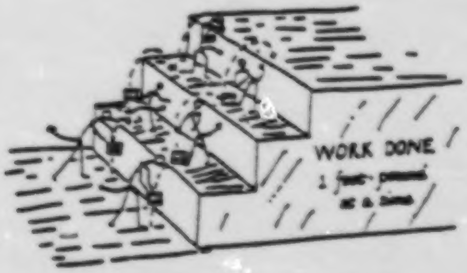

Figure 2. Work--Units demons do weight-raising job.

For load raisings, then, the total fuel demand could be measured by weight·height raised. And this is force·distance moved. Does that measure apply to other cases of engines using fuel to do jobs? If some engine hauls in a rope, we may make the rope raise loads or drag a cart or stretch a spring. Surmising that the engine will not know or care what the other end of its rope is working on, we expect to find the same amount of fuel used in every case for the same pull exerted and the same length of rope hauled in. So we shall now generalize weight·height into force·distance as a measure of fuel use.

We use the name energy for that something which fuel possesses in stored-up form and hands on through engines to raised loads, which again have something stored up which enables them to raise other loads if they fall themselves. In this way, energy is rather like money, which can exist in many different forms, can be stored in banks or put to use, and can be transferred to and from in many ways. We do not call the useful product force·distance moved energy, but name it work and regard it as a statement of transfer of energy, much as a bank check is a statement of transfer or money. (Some tests treat work as a form of energy, and distinguish between work done by a spring and work done on it. It seems better to take work, force·distance, as merely showing how much energy is transferred from one form or place to another. Then work has both a positive aspect and a negative one. It shows the energy lost by one agent, and the energy gained by another.)

INVESTIGATION 14: THE LEVER

A bank check is not itself money (nor is it wealth): it is just a statement of the amount of a transaction, of money lost from one account, money gained by another. Here we treat work as neither plus nor minus. It shows the energy lost by one party in some exhange, gained by the other. Note two things about this use of the word *work*:

a. It is much narrower than in ordinary talk, where we speak of working on a problem or of finding it hard work to hold a heavy load in our hand; though we also use *work* in the scientific sense, saying we do work when we *raise* a load. This is an unfortunate choice of a common word for a specialized use in science. We should have been wiser to invent a name for force·distance, just as the name *gas* was coined by the early chemists. (Whether concentrating on mathematical problems does use extra food-fuel, and why holding a heavy load in our hands is fatiguing, are physiological questions we shall touch on later.)

b. In multiplying force by distance, we must use the *distance moved along the direction of the force* (or, what amounts to the same thing; we may multiply the distance moved by the component of force *along the motion*).

   There is quite a different kind of force·distance in which the force and the distance are at right angles to each other. That measures the *moment* or *torque* or turning effect of a force around an axis, a useful concept in dealing with pulleys and levers.

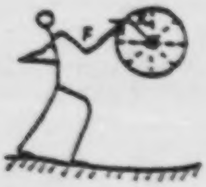

Figure 3

INVESTIGATION 14: THE LEVER

We can exert a moment (sometimes called a torque) by pushing against the spoke of a wheel. If the wheel remains at rest, no work is involved. We measure moments in pound·feet, to distinguish them from foot·pounds of energy. In the MKS system, moments are measured in meter·newtons, energy in newton·meters. Moments (torques), and their applications to levers and to production of spin-acceleration, are not treated in this course.

If we wish to be careful and precise, we combine reminders of (a) and (b) in the statements:

1. Work means, in science, force·distance moved by the point of application of the force, in the direction of the force.

2. Work, thus measured, shows the amount of energy transferred from one place or form to another.

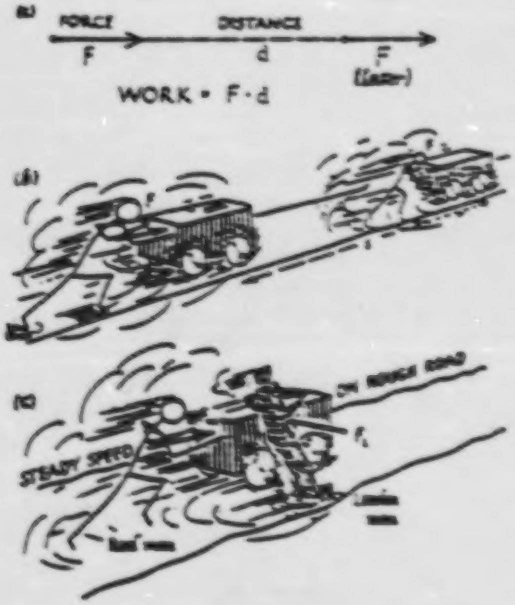

Figure 4. Work

(a) Work=F·d.

(b) A man pushing forward against the end of the cart transfers energy F·s whether he accelerates the cart or merely keeps it moving steadily on a rough road.

(c) The leaden man pushing sideways against the cart as it moves along does not help the motion. He need not use energy from fuel. If, on frictionless roller skates, he could just continue leaning on the cart. (The real man must push the cart to keep it moving steadily along the rough road. The force F_m does transfer energy: the force F_1 does not.)

Now we are beginning to describe energy clearly. It is the thing whose amount of interchange is measured by work.

Economy Schemes?

Fuel is terrifyingly important in our present civilization. In house heating and cooking, rapid transport, easy communication, all moving machinery for manufacture, we transfer the energy stored in vast quantities of fuel to other forms. Deprived of adequate fuel, commercial and civil life would be brought to a standstill and so would modern warfare. Food, the most necessary fuel of all, may yet be the limiting factor of all mankind's life in the very distant future--as it is now in many parts of the world. (See Sir Charles Darwin's fanciful but grave essay, The Next Million Years, New York, 1953.) Could we devise machines to save us using so much fuel? Levers and pulley systems can produce big forces from small ones.

Can such devices, machines as we call them in physics, also magnify our fuel resources and produce more energy from less fuel? We can insert a machine as intermediary between a fuel-using engine and the final job. Examine some typical schemes and see what help they give.

* Taken from Eric M. Rogers, Physics for the Inquiring Mind, Princeton University Press, Princeton, N.J., 1960, pp. 371-373.

INVESTIGATION 15: OTHER MACHINES — STUDENT GUIDE

Name________________________

Section_______________________

Introduction

Earlier you were told that the apparatus you used in Investigation 14 was a first-class lever and that it was a machine. The name first-class lever implies that there are other classes of levers. In this experiment, you are going to investigate other types of levers and other types of machines. You are going to begin by looking at some of the data you gathered in Investigation 14. That experience will help you understand the advantage in using machines. In other words, you will find the mechanical advantage of the first-class lever.

Exploration

Earlier you were told that the first-class lever was a machine. You can gain an understanding of why machines are used by looking at the data you gathered during that investigation. In Table I, list the amount of weight (W) that was lifted in Investigation 14, and the force (F) required to lift it. Make four entries in Table I. Also complete the third column in Table I.

Table I

W( )	F( )	W ÷ F	Work in (W_i)	Work out (W_o)	$\frac{W_o}{W_i}$

Study the column $W \div F$ in Table I. When is that value greater than one and when is it less than one? What is there about the first-class lever you used that changed when $W \div F$ changed from less than one to greater than one?

Complete the Work In (W_i), the Work Out (W_o), and the $W_o \div W_i$ column. What integer is the $W_o \div W_i$ closest to?

Write a summary of the data in Table I.

The Idea

$W \div F$ and $W_o \div W_i$ represent two important ideas. After a class discussion, describe each of those ideas here.

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Name________________________

Section______________________

Expansion of the Idea

Part 1: An Experiment

The diagram below shows a second-class lever. Notice the weight (W) is between the fulcrum and the force (F) which is lifted. You may have to hold the end of the lever on the fulcrum with your thumb. Begin by using a one kilogram weight (W). Place the weight at two different points along the lever arm (call the distance between the fulcrum and the weight d_2). Measure the force (F) required to raise the weight each time and the distance along the lever arm through which the force acts (d_1). Repeat the measurements using three kilograms. Enter all your data in Table II.

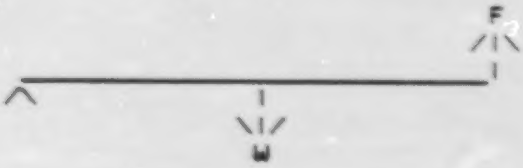

Figure 1

Table II

d_1 ( )	d_2 ( )	W ( )	F ( )	MA ( )	EFF ( )

Name________________________

Section_____________________

Expansion of the Idea

Part 2: An Experiment

This diagram shows a third-class lever.

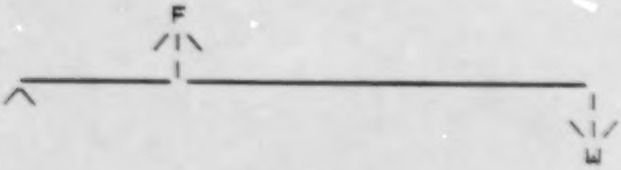

Figure 2

Use 1.0 and 1.5 kilogram weights and repeat the measurement you made with the second-class lever using the third-class lever. Four readings should be enough. Enter the data in Table III.

Table III

d_1 ( )	d_2 ( )	W ( )	F ( )	MA ( )	EFF ( )

Name________________________

Section______________________

Expansion of the Idea

Part 3: An Experiment

Set up the following pulley arrangements, using a one kilogram weight each time. Record the weight (W) lifted, the force (F) required, the distance the weight (d_w) was lifted, and the distance over which the force was applied (d_F) in Table IV.

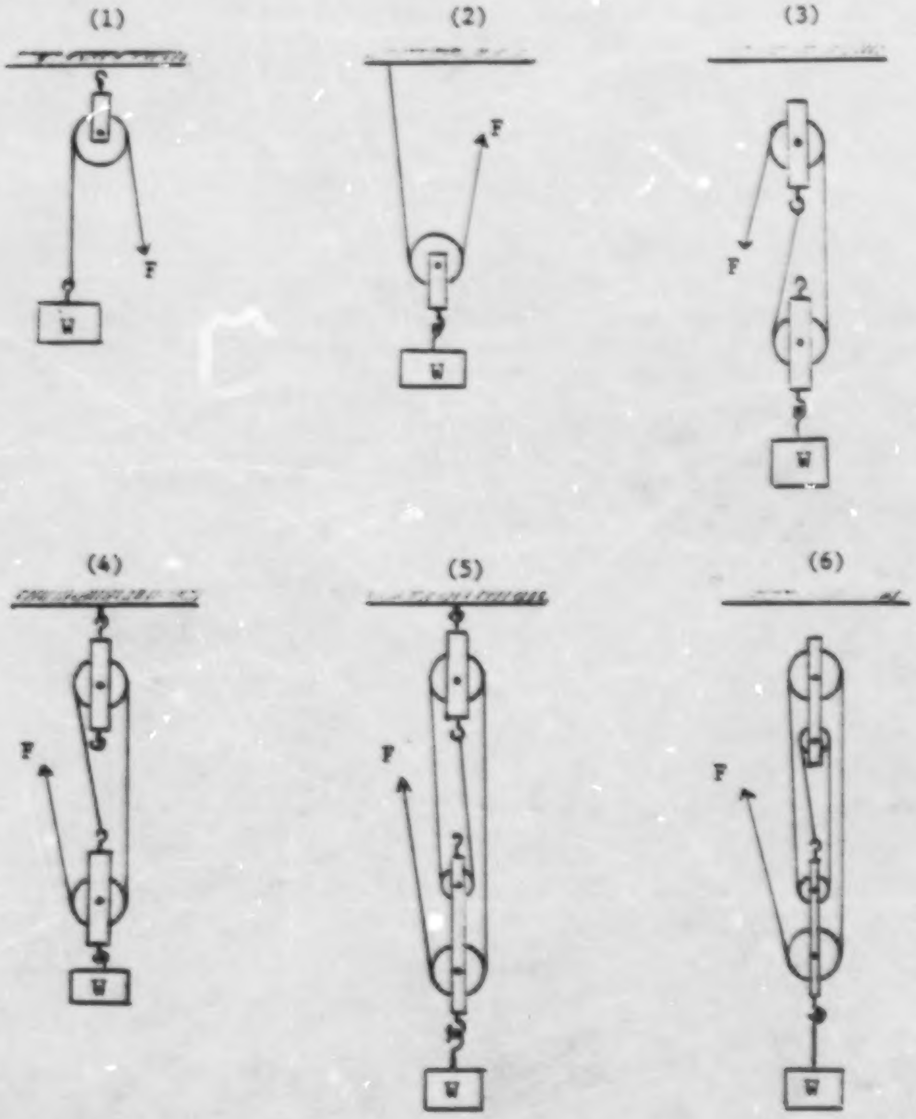

Figure 3

Table IV

Arrangement Number	W	dw	F	df	Work in	Work Out	MA	EFF
1								
2								
3								
4								
5								
6								

Explain what controls the MA of a pulley system.

____

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Examine the W_o/W_i (EFF) columns in Tables I, II, III, and IV. How do the values in those tables compare?

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Write a statement which relates the statement you just wrote to the energy in a mechanical system.

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Explain why the efficiency of the machines you used in this investigation is not always 100 percent. You may wish to review Investigation 13.

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Name__________________________

Section________________________

Expansion of the Idea

Part 4: Questions

1. Explain what the efficiency of a machine means and why it is computed by using (work out)÷(work in).

2. Explain why a wheelbarrow is a second-class lever.

3. A wheelbarrow and its load requires that 400 newtons of force be exerted on its handles. The distance from the wheel to where the force is applied is 1.5 m. The wheelbarrow and its load weighs 600 N. How far is the center of gravity of the wheelbarrow and its load from the wheel?

4. Describe a practical example of a third-class lever.

Name________________________

Section_______________________

Expansion of the Idea

Part 5: Reading Questions

1. A man wishes to lift a rock which has a weight of 100 N. If he uses a machine (for example, lever or pulley), will he be able to reduce the amount of work needed to lift the rock 5 m? Give an explanation for your answer.

2. How is a pulley like an equal arm lever?

3. In the reading, The Wheel and Axle, you determined that the mechanical advantage of the bicycle is less than one. What, if any, advantage do we derive from the bicycle?

INVESTIGATION 15: OTHER MACHINES

READING: MACHINES*

Lever or See-Saw

The see-saw may be treated as a children's toy or a device for balancing forces, as in weighing machines; but it can also transfer energy when it turns: pushing one end down makes the other end raise a load. Suppose an engine (using fuel) applies a force F_1 at A, one end of the bar ABC, pivoted at B (see Figure 1). Then the other end may support a much larger load at C. As the engine pushes A down, the big load is raised at C. But we calculate energy-changes by work which is not just force: it is force·distance. Suppose the end A moves down at distance D_1. Then the energy-transfer from the engine into the machine at A is $F_1 \cdot D_1$. The other end C pushes the load up with force F_2, rising a distance D_2. The energy transfer from the machine to the rising load at C is the work $F_2 \cdot D_2$. How do $F_1 \cdot D_1$ and $F_2 \cdot D_2$ compare? We shall find they are equal. If F_2 is many times bigger than F_1, then D_2 is just as many times smaller than D_1. Here is the argument. Simple experiments will show you the rule for balancing see-saws or levers if you do not already know it.

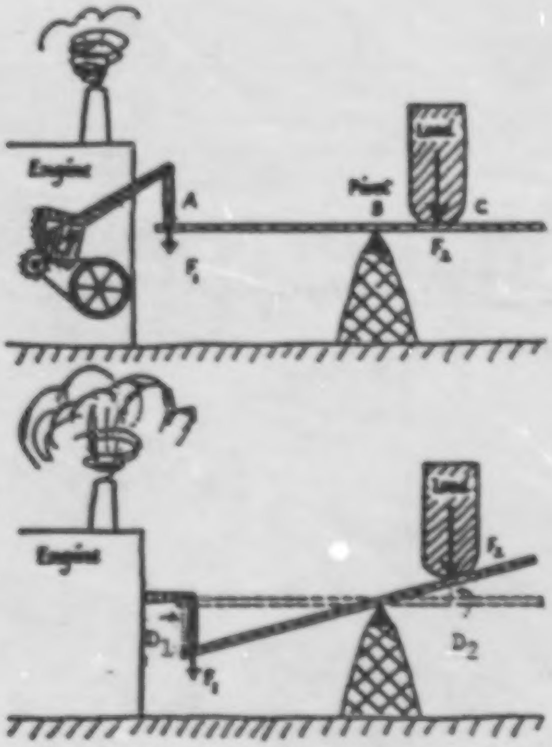


Figure 1. Engine Using Lever to Raise a Load

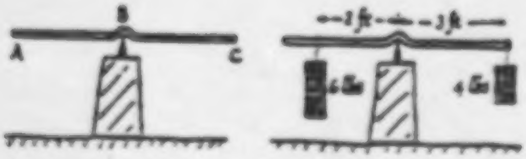


Figure 2. See-Saw for Testing the Balancing Rule
Force·Arm=Force·Arm

Figure 2 shows one case being tested. The bar ABC, pivoted at B, remains balanced in equilibrium, if left unloaded. Loads are added as shown, 4 pounds at 3 ft from the pivot and another load 2 ft out on the other side, to balance. For balance, the second load must not be an equal one, 4 pounds. Experiment shows the right load is 6 pounds. In this example,

4 pounds-weightx3 feet=6 pounds-weightx2 feet*
Force·Arm-Length = Force·Arm-Length

each arm-length being the perpendicular distance from the axis, B, to the line of action of the force.

* (these products are moments measured in pound·ft).

For this balanced lever,

$$\frac{\text{Force of 6 pounds wt}}{\text{Force of 4 pounds wt}} = \frac{\text{Arm-Length for force of 4 lbs wt}}{\text{Arm-Length for force of 6 lbs wt}}$$

The loads are in the inverse proportion of their arm lengths. Other specimen tests confirm the general rule. Just for interest, Figure 3 shows more complicated cases.

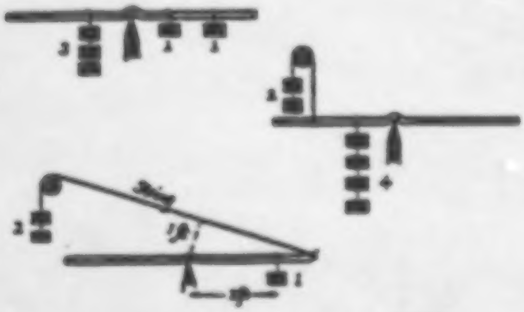


Figure 3. More Complicated Cases of Balanced Level. In each case, the total of the products (+ and −) Force·Perpendicular Arm from Pivot to Line of Force is zero.

Returning to the lever connecting engine and load, we know from experiment that the forces of F_1 and F_2 are in inverse proportion to the arms L_1 and L_2. That is, $F_2/F_1=L_1/L_2$. But by geometry, the distances moved, D_1 and D_2 have the same proportion as the arms, L_1 and L_2 (see the similar triangles shaded in Figure 4).

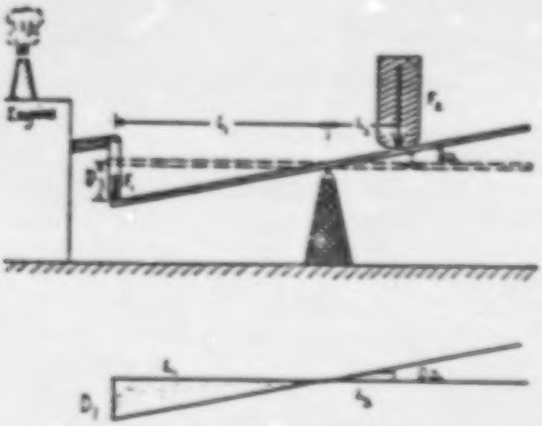


Figure 4. Sketch for Discussion of Machine

The shaded triangles are similar.Therefore, $L_1/L_2=D_1/D_2$. The load and effort really move in arcs of circles; so D_1 and D_2 are slightly curved, and the triangles are really sectors. But the same reasoning applies.

$$\therefore \frac{L_1}{L_2} = \frac{D_1}{D_2} \;;$$

$$\therefore \frac{F_2}{F_1} \quad \frac{L_1}{L_2} = \frac{D_1}{D_2} \;;$$

$$\therefore F_1 \cdot D_1 = F_2 \cdot D_2 .$$

Therefore, the two energy-transfers, the work $F_1 \cdot D_1$ and the work $F_2 \cdot D_2$ are equal. The work, $F_1 \cdot D_2$ is the energy-transfer from the lever to tho load. As $F_1 \cdot D_2 = F_2 \cdot D_2$, we say that the lever gains and loses equal amounts of energy.

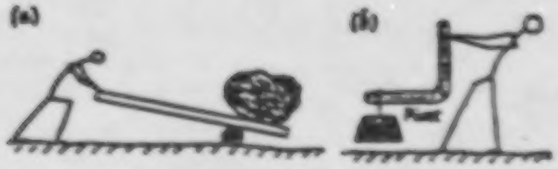


Figure 5. Levers can be useful. (a) Raise big load easily.
(b) Bent lever with equal arms.

The lever's input-energy and its output-energy are equal. As a machine, it merely hands energy on; it neither creates nor destroys any. This does not prevent a lever being very useful, to change the force to a more convenient size, or to alter its direction; but it does not solve the fuel problem. And, if there is friction at the pivot, there are tiny opposing forces and a little of the input-energy is wasted to some useless form.

Pulleys

A pulley wheel acts as an equal-armed lever. To show this, imagine the wheel to be of wood, with equal loads hung over it. Drive nails in at A and B to attach the rope to the wheel there. Then the rest of the wheel and the rest of the rope can be cut away, leaving an ordinary see-saw. To keep this balanced, the two loads must be equal; so we were correct in placing equal loads on the original wheel. If instead of one load, a man pulls on the rope, we still have a see-saw with equal arms, but one arm may now be bent up. In all cases, the rope tension is the same on both sides of the wheel. (If there is friction, the wheel will oppose turning, and the rope tension on the output side will be slightly less than that on the input side.) Remember tension in a rope is the pull at each end, and it is inward along the rope, at each end—a rope could hardly push.

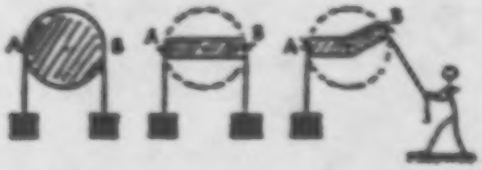


Figure 6. A Pulley is Like an Equal-Armed Lever

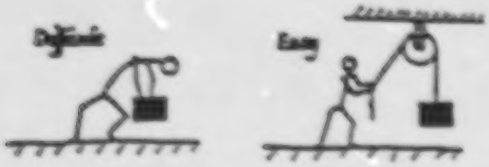


Figure 7. Pulleys are Useful. A pulley helps by changing the direction of force.

A pulley changes the direction of force, often greatly to our convenience, but if truly round and frictionless, it does not change the size of force. A single pulley, then, offers no hope of changing the value of force·distance. But what about pulley systems, wonderful block-and-tackle arrangements which enable a man to raise huge loads far beyond his ordinary strength? Investigate the system sketched, using common sense(=, as usual, experimental knowledge accumulated in nursery and ordinary life). The pulley system of Figure 8 is used by a man to raise a large load. What load can the machine raise if the man pulls down with a ten-pound pull? The pulley wheels act as equal-arm levers, changing the direction of the force, but not its size, except for friction. The ten-pound tension continues through rope A, over the pulley to B, and so on; 10 pounds-wt in ropes B, C, and D. Each of these is a tension, the force with which a rope pulls at each end. The total force exerted by the ropes on the load is the 10 pounds-wt. pull of rope B+10 pounds-wt. pull up of rope C+10 pounds-wt. pull up of D. That makes 30 pounds-wt. in all. For equilibrium--rest or steady motion--this must be balanced by the weight of the load. Therefore the man's 10-pound-wt. pull will raise 30 pounds, except for friction. In real pulleys, friction takes a small tax and 10 pound-wt. pull will raise less than 30 pounds. In general, this block and tackle arrangement gives a ration of 3:1, at best. This force ration,

$$\frac{\text{Load (=the weight of the load raised)}}{\text{Effort (=the pull exerted by the man)}}$$

$$\text{or } \frac{\text{output force}}{\text{input force}}$$

is often called the *mechanical advantage* of the machine. This set of pulleys, therefore, has a mechanical advantage of 3:1. This is its *theoretical* mechanical advantage, as an ideal frictionless machine. Its *practical* mechanical advantage will be less than 3:1, because of pulley friction.

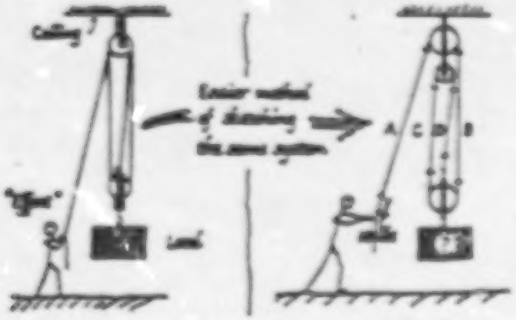


Figure 6. PULLEY SYSTEM: FORCE RATIO
Finding the force ratio (mechanical advantage) of a pulley system. The same tension continues through all the parts of the rope. The arrows show the rope tension pulling inward on man's hand, upward on load, etc.

Now compare the distances moved by pulling hand and rising load--or, compare their speeds of motion. For this, it is easier to start the argument at the load. Suppose the load is raised 1 foot. Pretend it rises by magic, letting the ropes develop slack loops. Then remove the slack by cutting out a one-foot length from each of the ropes B, C, D, and rejoining. If these three 1 ft lengths were not cut out, there would be 1 ft of slack in each of B, C, D, or 3 ft altogether. The load is really raised by pulling A down instead. Therefore the man must pull down 3 ft of slack. The distance ratio,

$$\frac{\text{Distance pulled by man}}{\text{Distance moved by load}},$$

is often called the *velocity ratio* of the machine, since it also gives

$$\frac{\text{Speed of man's rope}}{\text{Speed of load}}.$$

In this machine it is clearly 3/1. Once again *what is gained in force is lost in distance*.

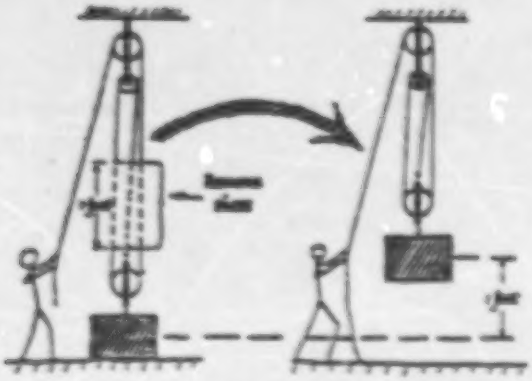


Figure 9. PULLEY SYSTEM: DISTANCE RATIO
Finding the distance ratio (velocity ratio) of a pulley system. Imagine the load rises one foot and calculate how much slack the man pulls down.

Now compare the energy transfers in our example: the input work is 10 pounds-wt. x 3 ft or 30 foot·pounds; the output work is, at best 30 pounds-wt. x 1 ft or 30 foot·pounds. Except for friction tax, the machine neither creates nor destroys energy, but only transmits it, transforming the force of our arm pull to a bigger force for our convenience. With friction, some of the input energy seems to disappear--diverted into heat.

* Taken from, Eric Rogers, Physics for the Inquiring Mind, Princeton University Press, Princeton, N.J., 1960, p. 373.

READING: THE WHEEL AND AXLE

In the past two investigations, you have been examining two types of machines--the lever and the pulley. One generally desires to use these machines because they allow lifting large loads with less effort. Of course, as you know, one must still do the same amount of work because the distance over which the load is moved is increased. The third class lever is an exception to that pattern, as the force acts over a very small distance and is, thus, very large.

Another type of machine closely related to the lever and pulley is the wheel and axle. The simplest example of a wheel and axle is a large wheel and cylinder turning on the same axis. The relation to the lever is clear; the center of the axle is the fulcrum and the lever arms correspond to the radii of the wheel and the axle.

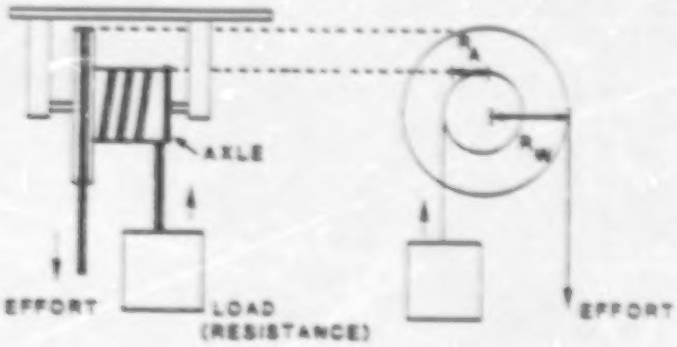


Figure 10

The advantage of the wheel and axle is likewise similar to a first-class lever in that it allows one to lift heavy loads with little effort. The force is exerted by pulling down on a rope or turning a crank with a large radius--thus, the force acts through a large distance. The load can then be lifted with less effort. We can symbolize this relationship by the equation:

$$\frac{\text{Load}}{\text{Force}} = \frac{\text{Radius of Wheel}}{\text{Radius of Axle}}$$

You will note that this equation is analogous to the equation you developed for work in a lever or pulley. In the lever, the radius of the wheel is replaced by the distance of the force and the radius of the axle is exchanged for the distance the load is moved.

How would you find the mechanical advantage of a wheel and axle? You know from your work with the lever that the ideal mechanical advantage (IMA) of a machine is derived from some data concerning the machine. In the wheel and axle, the IMA is found by the ratio:

$$\text{IMA} = \frac{\text{Radius of Wheel}}{\text{Radius of Axle}}$$

The actual mechanical advantage (AMA) would be calculated from the usual ratio:

$$\text{AMA} = \frac{\text{Load}}{\text{Force}}$$

You use many types of wheel and axles in your daily life. Pencil sharpeners (where the wheel is the handle), cranks that are used to bring your boat out of the water and windlasses are some examples. But probably the most important example may not occur to you at first--the bicycle. The bicycle is actually composed of two intertwined wheels and axles. First, the pedal connected to the sprocket that turns the wheel is a wheel and axle. Also, the sprocket and the wheel is a wheel and axle. In the latter case, the wheel of the bicycle is actually the axle of the wheel and axle. Confused? Remember that the wheel is the portion of the wheel and axle upon which the force is exerted.

Compare the mechanical advantages of the bicycle and the third-class lever. What do they have in common? Well, you know from your data in Investigation 15 that the MA of the third-class lever is less than one. Now consider the sprocket and wheel (wheel and axle) of the bicycle. If you use the equation R_W/R_A, you find that (since the radius of the sprocket is much less than the wheel) the IMA of the bicycle is less than one. But, you say, the bicycle is a very important machine! Sure it is, but its mechanical advantage is less than one. So the fishing pole (a third-class lever) and the bicycle are two useful machines from which we do not obtain an advantage in terms of load/force. What is the advantage then? That we will let you determine.

INVESTIGATION 16: THE INCLINED PLANE STUDENT GUIDE

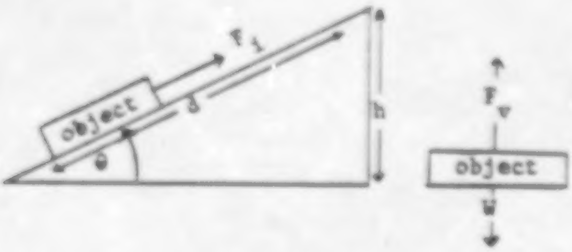
Name____________________

Section____________________

Introduction

So far, you have investigated the lever which is one class of simple machines. You also studied the pulley which is a first-class lever. There is a second type of simple machine called the inclined plane. That machine is simply a plane which has one end higher than the other. It is used to move objects diagonally to a higher point rather than lifting them straight up from one point to another. Ramps and stairs are examples of inclined planes. You will need to use the relationships for efficiency and mechanical advantage you used in the last investigation.

Exploration



The diagram shows all the variables associated with the inclined plane. Those are the variables with which you will experiment. List the values you measure for each variable in Table I. List the units of measure for each variable at the head of each column in Table I.

Figure 1

Where: θ=angle of the plane to the horizontal
h=height of the plane
W=load moved up the plane
F_i=force exerted up the plane
F_v=force exerted vertically to lift the load straight up
d=length of the plane

Table I

θ( )	h( )	W( )	F_i( )	F_v( )	F_i/F_v ( )	d( )	Wo/Wi	W/F_i

Set the angle, θ, on the inclined plane. Record that value. Do not change that angle during each series of measurements. Weigh the object and record its weight, W. Fasten the spring balance to the object and lift it straight up through a distance equal to the height, h, of the plane. Read the force, F_v, necessary to lift the object. Record h and F_v. What does the product hF_v represent? (Be sure to support your answer with evidence.)

Measure the length of the incline, d, and record that value in the table. Attach the spring balance to the object and pull the object up the plane. Be sure the force needed to pull the object up the plane, F_i is exerted parallel to the plane. Record the value for F_i. Now add one kilogram of weight to the object and repeat the measurements you have just taken. Keep the angle, θ, of the plane the same. Next change the angle, θ, of the plane and repeat the experimental process exactly as you first did. When you have complete data for the second angle, write a summary of the data collected.

When you have complete data for the second angle, write a summary of all the data collected.

INVESTIGATION 16: THE INCLINED PLANE STUDENT GUIDE

Name______________________

Section______________________

The Idea

1. What is the mechanical advantage of the inclined plane?

2. Compare the efficiencies of the inclined plane, pulley, and levers.

3. What does $F_i d$ represent?

4. What evidence do you have to support your answer?

5. How do $F_i d$ and $F_v h$ compare?

6. What is the efficiency of the inclined plane?

___

___

___

7. What might be some reasons why the efficiency of the inclined plane is different from the efficiencies of pulleys and levers?

___

___

___

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Name______________________

Section____________________

Expansion of the Idea

Part 1: An Experiment

Experiment, changing the variables in the inclined plane to find out whether or not you can increase its mechanical advantage or its efficiency. Design a table to record your data. Remember to change only one variable at a time.

Name______________________

Section______________________

Expansion of the Idea

Part 2: Problems

The following problems are based upon the diagram shown here. There are three machines being used together in pulling the boat out of the water.

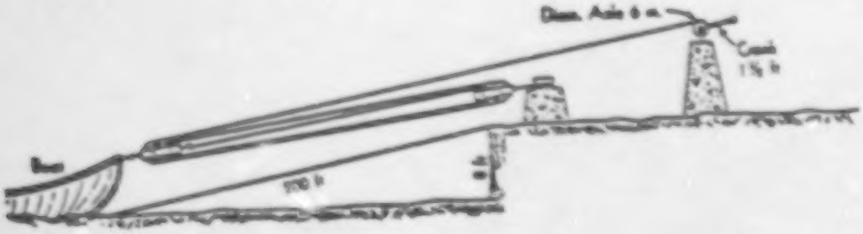


Figure 2

1. What are the three machines being used?

____

____

____

2. Find the mechanical advantage of each machine.

3. Explain how many times the force applied to the crank will be multiplied in moving the boat out of the water.

4. Suppose 50 pounds were applied to the crank. How heavy a boat could be moved up the incline?

Name________________________

Section________________________

Expansion of the Idea

Part 3: Reading Question

The last paragraph of the reading, The Inclined Plane, tells you that "screws and wedges are simple machines that have low efficiencies due to large frictional forces, but have large mechanical advantages." Explain how this is possible.

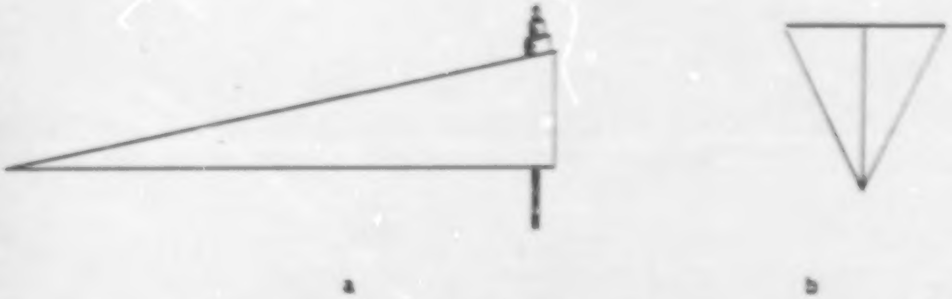
INVESTIGATION 16: THE INCLINED PLANE

READING: USING THE INCLINED PLANE

At first thought, you may consider the uses of inclined planes to be limited. Ramps (a layman's term for inclined planes) are found in athletic stadiums and on shipping docks. One could also think of a road going up a hill as being an inclined plane. Well, it appears we have three uses for inclined planes: herding fanatics, loading barrels, and driving to Inspiration Point. Not exactly what one would call universal usage.

Things are not always what they seem, however. If you took a very thin inclined plane (for example, one cut from paper) and wrapped it around a pencil, you would still have an inclined plane, but now it would be called a screw. (see Figure 1 a) If you took two inclined planes of equal dimensions and placed them base to base, you would have a wedge. (See Figure 1 b) The screw and wedge are two types of inclined planes; each has many uses.

Figure 1



a

An inclined plane wrapped around a cylinder may be thought of as a screw.

b

Two inclined planes placed base to base can represent a wedge. A single inclined plane can also be thought of as a wedge.

The screw is an inclined plane wrapped around a cylinder or core. The spiral part of the screw that digs into the wood or other building material is called the thread. The cylinder itself is called the body; the axis is the center line of the body. As you turn the screw into a piece of wood, the wood moves along the axis traveling from crest to crest along the threads. The distance between the crests is called the pitch (see Figure 2).

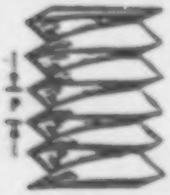


Figure 2

The purpose of the screw is to raise a load over the threads of the screw by applying a small force. Thus, the screw is a machine as it allows one to exert less force over a greater distance to do a certain amount of work. Since there are no other machines contributing to the work done by the screw, the screw is called a simple machine. (When two or more machines are used at the same time to perform a task, the combination is called a compound machine.)

How could one determine the amount of work done by a screw? You know that work is found by multiplying the force applied by the distance moved. Each turn of the screw moves through a distance of $2\pi r$ (which is the circumference of a circle). The force applied to the screw times the circumference equals the work done per revolution. To determine the total amount of work done when the screw was completely inserted in a piece of wood, you would multiply the number of complete turns by $(2\pi r)(F)$.

If you have ever touched a screw that has been recently removed from a piece of wood, you know that turning the screw generates heat. The heat is due to the frictional forces that exist between the screw and the wood. Although friction is a disadvantage in many situations, it is an advantage in the case of the screw. The force of friction actually increases the "bite" of the screw and helps hold it in place. However, you know that friction is a force opposite the force applied to the machine. Therefore, you must apply enough force to more than counteract the force of friction.

INVESTIGATION 16: THE INCLINED PLANE

Your experience with machines has shown you that as friction increases, the efficiency of the machine decreases. Does the friction between the screw and the wood negate that advantage of this machine? To answer this question, let us consider a special type of screw--the jackscrew. The jackscrew is actually a combination of a screw and a lever (so it is a compound machine), but it will serve our purpose. Figure 3 shows you a picture of a jackscrew. The jackscrew is operated by turning the lever arm so it moves in a large circle with a circumference of $2\pi r$. One turn of the lever arm will move the screw a distance equal to the pitch of the screw. If a jackscrew has a pitch of 1/3 inch and is operated by a lever which moves through a distance of 36 inches, the mechanical advantage of the screw will be: $MA=(d_{lever})/(d_{pitch})=(36\ in)/(1/3\ in)=108$. Although the friction is high and the efficiency is consequently low, the mechanical advantage is so large the machine has many uses.

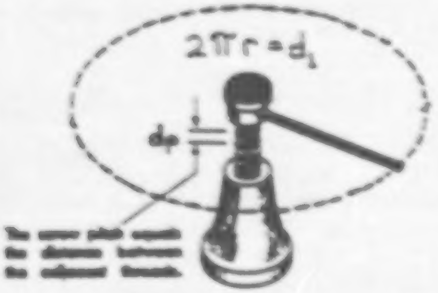

$2\pi r = d_1$
d_p
The screw pitch equals the distance between the adjacent threads.

Figure 3

The jackscrew is a combination of a screw and lever. The distance the lever travels is designated as d_1. The pitch distance of the screw is noted as d_p.

Many kinds of screws are employed in daily activities. Besides the screws used to fasten pieces of wood together, there are adjustable piano stools, spiral staircases, and the feeding mechanism on food grinders. The propellers on ships and airplanes are giant screws that bite into water and air and produce the movement of these large vessels.

A second type of inclined plane is the wedge. Knives, hatchets, chisels, scissors, and icepicks are all kinds of wedges. Wedges are also used to prop doors open and prevent the heads of hammers from flying off the handles? As in the case of the screw, the friction between a wedge and what is being wedged into is great. However, this friction is necessary in the action of several types of wedges.

INVESTIGATION 16: THE INCLINED PLANE

The purpose of wedges such as chisels and icepicks is to spread the surface being worked on a certain distance by exerting a force on the wedge. If a chisel has a blade length of 1 cm and a diameter of 1 cm, the surface will be spread apart 1 cm when the chisel has been inserted 1 cm into the material. Depending on the material being chiseled, a certain amount of resistance will be encountered when the chisel is being driven. It certainly would have been easier for Michelangelo to chisel the statue of David from soft pine rather than from marble.

Wedges such as those used for door stops do not noticeably separate the surfaces they are wedged between. These wedges utilize the large amount of friction produced when they are hammered or kicked into place. A large force is then required to move the door against the action of the wedge. The friction is so great that a relatively small wedge can prop oven a very heavy door. You would need to place a very massive brick in front of the door to keep it open. Thus the advantage of the wedge becomes apparent.

Our list of uses for the inclined plane has grown dramatically. We use one or more kinds of screws and wedges every day. Screws and wedges are simple machines that have low efficiencies due to large frictional forces, but have large mechanical advantages. In addition, the friction is actually an advantage in many instances.

INVESTIGATION 17: ENERGY

STUDENT GUIDE

Name__________________________

Section________________________

Introduction

In Investigation 14, The Lever, you were introduced to the ideas of work and energy. You found that work was the product of a force moved through a distance when the force and distance were parallel and in the same direction. Also, you were presented with the idea that the property of a system that enables it to do work is energy.

You know that work is measured in units of force and distance (newton-meters or joules). Since its energy enables a system to do work, energy and work are equivalent. They are, therefore, measured in the same units--newton-meters, foot-pounds, etc.

Exploration

This is a think investigation. There may be several places in the investigation where you will want to check a result. The equipment necessary to check a particular result will be available to you.

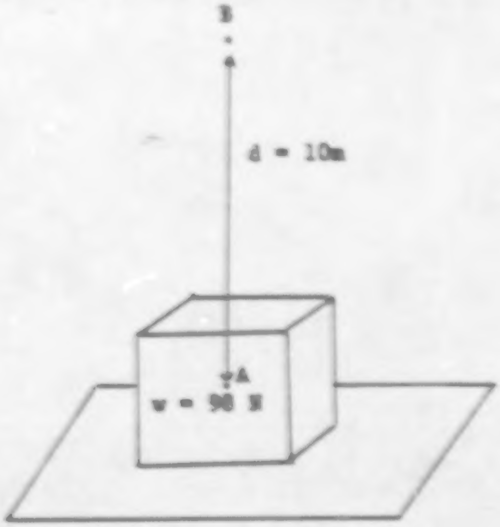


Figure 1

INVESTIGATION 17: ENERGY STUDENT GUIDE

1. Figure 1 shows a box which weighs 98 N resting on a horizontal surface. The box is to be lifted until its center of gravity--point A--reaches point B. That distance is 10 m. How much work will be done in lifting the box?

2. In Investigation 16, The Inclined Plane, you were introduced to the idea of the conservation of energy. State the conservation of energy principle here.

3. You know that work and energy are equivalent. How much energy does the box have at point B that it did not have when resting on the horizontal surface?

4. The box will now be dropped to the floor. What will happen to the energy?

5. What will the energy probably do to the floor and the box?

The Idea

1. In other words, the box has the ability to do work when it is at point B. What is a single word that means has the ability to?

   ____

2. Write an equation that will always permit you to compute the type of energy you just named.

   ____

   ____

3. The type of energy you just named is sometimes called the energy of position. Why is that possible?

   ____

   ____

Name________________________

Section______________________

Expansion of the Idea

Part 1: Questions and Problems

1. When force is exerted to lift the box, what is that force overcoming?

2. Add that name to the name of the energy type you invented in the last section. Write that complete name here.

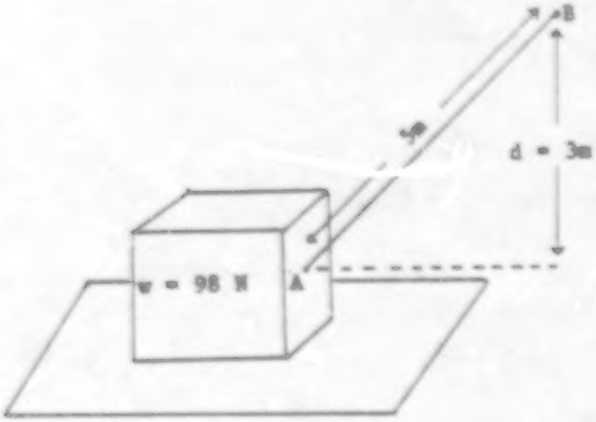


Figure 2

3. Figure 2 shows a 98 N box resting on a horizontal surface. How much work is done in raising the box until its center of gravity, Point A, meets Point B?

4. Explain why you solved the problem the way you did.

5. Refer back to Figure 1. Write the equation for the amount of work that is done in moving the box from A to B. Do not solve that equation numerically.

6. The box now has energy which equals the amount of work done on it. That is a special kind of energy which has a specific name. Rewrite the work equation as an energy equation using that specific name.

7. You are going to write a series of equations about how the energy of the box changes as it moves from B to A. Do not give numerical solutions to any of those equations except in answering the next question.

   a. What is the initial velocity of the box just as it begins the fall from B to A? $v_1=$

   b. What would be the velocity, v_2, of the box when it struck the floor: $v_2=$

   c. What is the acceleration with which the box moves toward the floor? a=

   d. What is the force with which the box strikes the floor? F=

8. Use the specific energy equation you wrote above and the values for v_1, v_2, a, and F that you just wrote. Write an energy equation for the box as it strikes the floor.

9. Suppose a load of 1000 kg were to be lifted 10 meters straight up against gravity. How much work is required to do that job?

The equation work=Fd gives the total amount of work done in doing any job; it says nothing about the time needed to do that job. The job may be done in an hour, a day, or a week, but the same amount of work is required.

Suppose that the work was first done in ten minutes and then in one hour. That means that the total amount of energy delivered must be delivered much more rapidly in the ten minute period than in the one hour period. The rate at which energy is supplied is called power. So if the work needed to lift the 1000 kg load ten meters is performed in ten minutes, more power is required than if that same amount of work were supplied in one hour.

Power, therefore, is energy supplied per unit of time. Its units are newton-meters per second, foot-pounds per hour, or any combination of units of energy per unit of time. A newton-meter/sec is a watt and 550 foot-pounds per second is one horsepower.

10. How many watts are there in one horsepower?

11. Write an equation for power.

Name________________________

Section______________________

Expansion of the Idea

Part 2: Problems

1. A 2.00×10^2 kg iceboat is supported by the smooth surface of a frozen lake (neglect friction). The wind exerts a constant force of 4.0×10^2 N on the boat while the boat moves 9.0×10^2 m. The boat starts from rest. Find the speed attained at the end of a 9.0×10^2 m run by each of the following methods.

   a. Find the acceleration of the boat. Find the time it takes to go 900 m. Find the final velocity.

   b. Find the final speed by equating the work done on it by the wind with its increase in kinetic energy. Compare your result with your answer in a.

2. A rock, mass 50 kg, falls off a cliff 20 m high.

   a. What is its gravitational potential energy before it falls?

   b. What is its kinetic energy just before it lands?

   c. Use conservation of energy to find its speed just before it lands.

   d. After it has fallen 10 m, what is its gravitational potential energy and what is its kinetic energy?

3. How much work is done in changing the velocity of a 5.0×10^3 N car from 20 m/sec to 30 m/sec?

4. A 2.0 gram bullet is shot into a tree stump. It enters at a speed of 300 m/sec and comes to rest after having penetrated 5.0 cm in a straight line.

   a. What was the change in the bullet's kinetic energy?

   b. How much work did the tree do on the bullet?

   c. What was the average force during impact?

5. An ocean liner has a mass of 75×10^6 kg, maximum engine power of 174×10^6 watts, and a maximum speed of 16 m/sec.

   a. What is the liner's kinetic energy at full speed?

   b. Assume that at maximum speed, all power goes to overcoming water drag. If the engines are suddenly stopped, how far will the ship coast before stopping? (Assume water drag is constant.)

Name________________________

Section_____________________

Expansion of the Idea

Part 3: Reading Questions

Why would a perpetual motion machine violate the conservation of energy law?

INVESTIGATION 17: ENERGY

READING: ENERGY*

What is Energy?

We have not described energy clearly yet, and we may never be able to give a crisp definition. But you should now begin to feel familiar with energy from our discussion of jobs and fuel and work. In time, this acquaintance should mature into a clear understanding. As with your understanding of other general concepts such as Justice, Kindness, Love, we may never be able to agree on a definition, yet you will rightly claim, "I know perfectly well what it means; I *understand* it." For the present, you should think of *energy* as *something supplied by fuels, something which can be interchanged between several forms,* and *something whose interchange-amount is measured by* force *multiplied by* distance. Work measures interchange of energy. So the official definition of energy says, *energy is capacity for doing work*. Qualitatively, this is not a very helpful description; it merely says "a thing that has a lot of energy is able to give a lot of energy to something else." Quantitatively, this definition tells us to measure energy in the same units as work.

Units for Energy

Since we measure transfers of energy by force·distance, which should have units

(lbs-wt) (feet) or (kg-wt) (meters) or (newtons) (meters)

we use these units for energy, writing them

foot·pounds   kilogram·meters   newton·meters

The first two involve *bad* force units. They are much used in engineering, but we cannot use them in connection with F=Ma--so they are unsuitable for the energy of moving bodies. The third unit, a *newton·meter*, is a *good* unit. It is used so much that we shorten it to a new name and call it a *joule.* Thus, saying that 1 newton meter=1 joule is no new science; it is mere dictionary work. Since 1 newton is roughly 1/4 pound-wt. and 1 meter is roughly 3 feet, 1 joule is roughly 3/4 of a foot·pound; (more accurately 0.74).

INVESTIGATION 17: ENERGY

Foot·pounds and kg·meters contain (bad) force units. They mean foot·*pounds-weight* and *kilograms-weight*·meters, but the *kilogram* concealed in newton·meters is a mass unit.

We still have no way to measure the total energy in some stock--whatever *total energy* means. We can only measure certain interchanges, using force·distance or work as a measure of the amount of energy transferred. Then energy-changes are measured in joules, ft·pounds, etc.

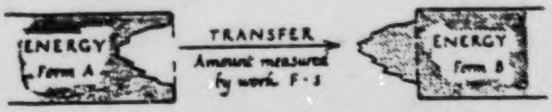


Figure 1. Work

Forms of Energy

Watching the energy interchange when jobs are done and measuring its amount by the work product force·distance, we can describe several forms of energy. A wound-up spring has a store of *elastic energy* or *strain energy*. A load raised higher above the earth has gained *gravitational energy*. Oil and gasoline have *chemical energy* that can be transferred to gravitational energy when they drive a machine that raises a load. Fireworks and explosives have *chemical energy* that can be released suddenly. Food has *chemical energy*, some of which our bodies turn into elastic energy or gravitational energy when we use muscles to wind springs or raise loads.

A moving truck has energy on account of its motion, because it could raise loads if attached to suitable ropes and pulleys, but it must lose its motion in doing that. And *chemical energy* in an explosive may end up in energy of motion in a bullet. We call that energy of motion *kinetic energy* (from the Greek for motion; same origin as cinema). Notice that already we are telling stories about energy which assume that it is never created or lost but only transformed.

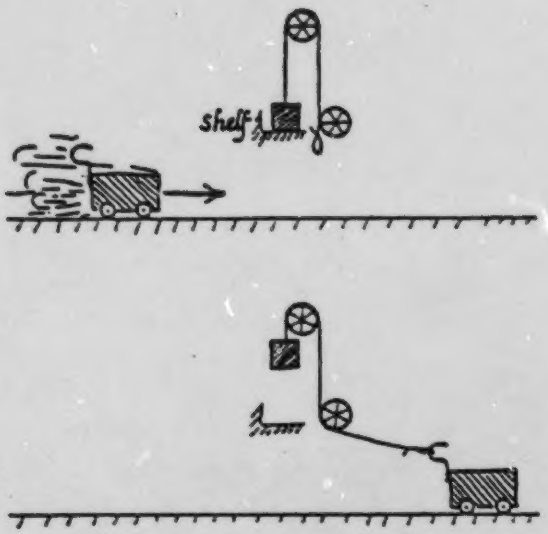


Figure 2. Changing K.E. to P.E. The moving truck is hitched to a load that it can raise. In raising the load, the truck comes to rest.

If a truck is shifted from one place to another place at the same height above ground, there is no change of gravitational energy. If it starts and finishes at rest, we can imagine the move made free, with no net transfer of energy. We pretend we give the truck a little kinetic energy (borrowed from some store of gravitational or chemical energy) and let it run along a frictionless level road to the new place. We bring it to a stop there, taking away the kinetic energy (and repaying the store).

We find that a truck moving with kinetic energy along a rough floor comes to rest without raising weights. Has its energy been destroyed or only transferred? Maintaining our belief, we look for the energy in some new form. The rubbing of rough surfaces has produced heat. Can we speak of heat energy too? Early studies of heat did not show it as a form of energy. Heat was regarded as a mysterious and indestructible fluid, like our present view of electricity. A great series of experiments in the last century showed that heat is a form of energy. And now the scheme has been extended to still more forms, a grand system of energies adding up to a constant total, in any enclosed region...

Perpetual Motion

Simple machines such as levers and pulleys transform the size of force and the speed of pushing or pulling, often greatly to our comfort; but the ultimate fuel-demand, measured by force·distance, is the same--or even greater on account of friction-tax. Useful energy output from a machine equals energy input to it, less some friction-tax. Yet for centuries men have wanted to save using fuel, and the temptation and hope are as strong as ever. Perhaps pulleys and levers are too straightforward. Could a more ingenious machine give out more energy than it takes in? This was the search for perpetual motion, now numbered among the seven follies of science.

Such a machine would indeed make its inventor's fortune: it could change the course of civilized life. We speak of such machines as perpetual motion machines; and we are now convinced that they can never succeed. The name perpetual motion is unfortunate because it misleads people into thinking that the essential problem is to remove friction and thus obtain what we might call, to distinguish it, perpetual movement. If that is all, we can nearly succeed with a wheel spinning on ball bearings, and nature does succeed with the spinning earth and the moving planets, atoms, etc. These cases of perpetual movement would soon fail as perpetual motion schemes; if we tried to take energy from them, they would slow down and stop.

A perpetual motion machine would, of course, run of its own accord, taking any little payment needed for friction-tax from its own extra output. But the essential characteristic of the hoped-for device is not just continual running, a steady spinning--that would be mere perpetual movement, pretty but useless. To bring lasting fame and rich rewards it would have to do more than keep running steadily, with its output just feeding its input. Its output would have to exceed its input; so that it could supply its own input and still have some output left over to do useful jobs free of charge. It would have to yield a continual profit of energy without fuel. It should be able to run steadily while lifting loads; or if left unloaded, it should run faster and faster. Such motion, providing a continual supply of energy from nowhere, is what we call perpetual motion. Could such a machine be made? For centuries, this problem has offered great rewards for success, tempting the clever thinker, intriguing the ingenious designer, taunting the conqueror of nature. All efforts have failed. There is always a catch. Solutions have been offered by well-meaning scientific inventors, and by cheating charlatans. Business investors have been tempted by hopes of fabulous wealth; and some have risked their money, and lost it when the machine failed or its inventor absconded. In the course of time, suggestions grew more complicated; simple wheels with swinging spokes or sliding loads gave place to engines using complex gears, schemes for making an electric generator and motor run each other with profit, and even an alluring use of liquid air. (A motor and generator can almost keep each other running--perpetual movement--if no external demands are made. The motor drives the generator by a belt and the generator supplies current to run the motor, with a little help from a battery to pay for friction and heating of wires. This is used as an economical scheme for testing big machines.) All that were actually tried failed, failed to deliver a continual stream of energy without using further fuel. Those that were examined critically without being tried in a working model have all shown some catch, so that our general knowledge predicts failure. Scientists now feel so surely convinced that perpetual motion (in its special sense) is impossible that they now state their belief as a general Principle, often called the First Law of Thermodynamics.

If we believe mechanical perpetual motion is impossible, we are halfway to assurance of conservation; machines cannot create energy, but they might destroy some. Only when we account for heat etc. as well, do we gain complete assurance.

What view should you yourself take? Should you continue the search for perpetual motion yourself, or obediently accept scientists' dogmatic denial? In view of the evidence, the latter seems wiser. For once, we do not encourage you to start with doubts and do your own experimenting. However, in a way you are surveying the results of experiments when you pay your bills for gasoline or electric supply; machines to replace fuel have failed. Satisfy yourself, by arguing them through, that arrangements of levers and pulleys cannot be turned into a perpetual motion machine; and try to find the catch in diagrams of some of the more complicated devices suggested as perpetual motion seems utterly unlikely, unthinkable, impossible, against nature.

Note that this statement brings no proof. It is a mixture of a summary of experimental tests and a statement of faith. Scientists fully familiar with the interlacing threads of evidence hold this view confidently.

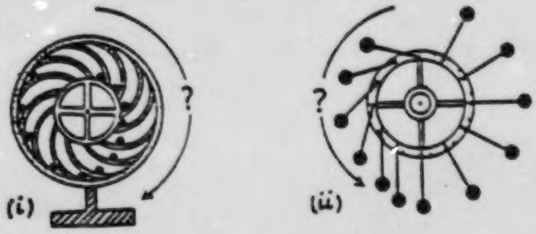


Figure 3. Perpetual Motion Machines. Two simple proposals (i) A wheel carries balls in curved compartments. (ii) A wheel carries weights on spokes pivoted between stops on its rim.

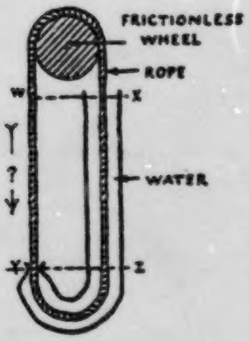


Figure 4. Perpetual Motion Machine. An endless loop of rope partially immersed in water. (The joint at Y should be frictionless, yet leakproof; but this requirement is NOT the essential catch.)

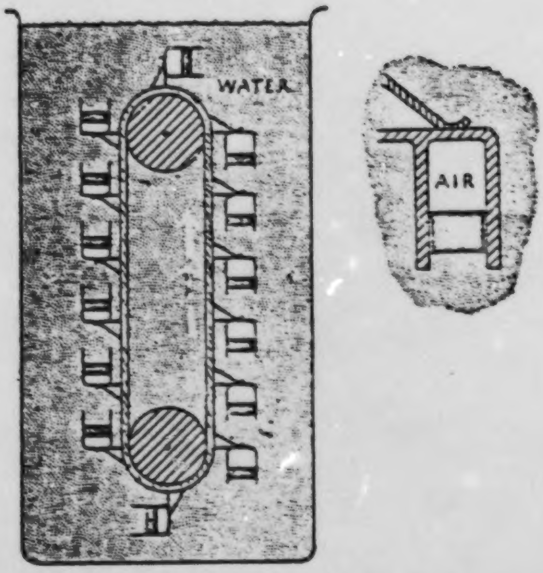


Figure 5. Perpetual Motion Machine. An endless belt on frictionless pulleys under water carries cups with air enclosed by a heavy frictionless piston. Where the cups are upright (on left), the weight of the piston compresses the air more than where they are inverted. Therefore, the cups on the left displace less water than those on the right and should experience smaller buoyant force. (The pulleys should be frictionless and so should the pistons, but this requirement is NOT the essential catch.)

Yet in this century, two other strong scientific beliefs have been broken: we can now create and destroy matter, and we can now change one chemical element into another--we should stop calling the alchemists' dream of turning lead into gold another of the seven follies of science. Why, then, are we so sure that energy is conserved, and perpetual motion impossible? That is partly because the evidence is so plentiful and varied; partly because the idea of energy is an artificial one, moulded to fit our impressions of the outside world and our thinking about it. So, unlike matter, which we might say just is there, energy is our own idea and we shall choose to preserve it even if we have to change the design from year to year. Yet each extension of our scheme of energies, however fantastic a guess at first, has in the course of time met test after test of validity. The Conservation of Energy does tell us something very valuable about the Universe.

* Taken from Eric M. Rogers, Physics for the Inquiring Mind, Princeton University Press, Princeton, N.J., 1960, pp. 379-382.

INVESTIGATION 17: ENERGY

READING: TWO ENERGY SOURCES*

Chemical Energy

When an explosive is fired, it produces hot gases which in turn can give a bullet kinetic energy. In this case, the bullet collects organized K.E. at the expense of the heat in the hot gases (their disorganized K.E.). How do the gases obtain the heat energy, which they give to the bullet? Before the explosive is fired it is cool solid holding chemical energy. The energy in our primary fuels--coal, wood, oil--is chemical energy. This is molecular energy, stored if you like to think of it so, in the fields of force between atoms. You might picture a chemical compound being made by shoving the atoms into place in molecules against springy interatomic forces and latching them there, with potential energy stored in compressed springs. Of course chemical energy is really a much more complicated matter than this crude model, but the overall picture is clear: atoms and molecules do store energy which can be released in some chemical changes and taken in and stored in other changes. Most fuel releases its energy when

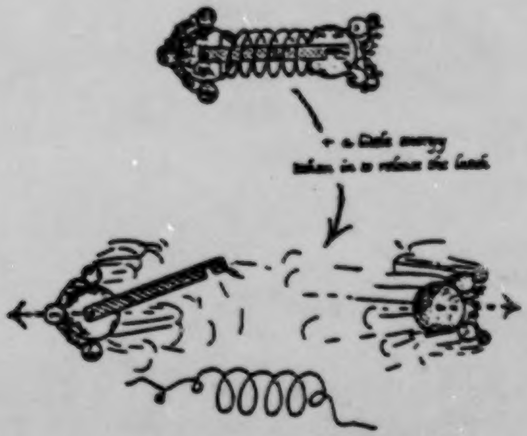

+ a little energy
taken in to release the latch

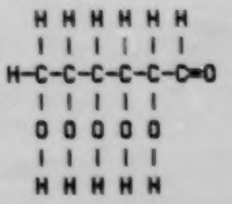
Figure 6. Fanciful Picture of a Molecule of Explosive to illustrate description in the text. (A more genuine model would have no latch but another spring in tension, in equilibrium with the compression spring but with a different law of force. Even with a scheme like that, models of fuel burning with oxygen are clumsy and unreal.)

it burns with oxygen; so fuel energy relates to the force-field between fuel molecules and oxygen. It is difficult to picture its location, though its amount is definite enough because we can measure the work, force·distance, when it is transferred to other forms: so much transfer for every pound or kg of fuel burned completely. The chemical energy in a firework or explosive is easier to locate. It is all there, stored inside the molecules of material.

Food: A Supply of Chemical Energy

Food is fuel for man or beast; it provides chemical energy which is carried by the bloodstream to muscles which need it. The muscles can transform some of the food-energy reaching them into mechanical energy for raising weights, etc.

Foodstuffs contain fuel molecules, mostly made of carbon, oxygen and hydrogen atoms. For example the simple sugar dextrose which runs muscle action is $C_6H_{12}O_6$ or



$$\begin{array}{ccccccccccccccc} & & H & & H & & H & & H & & H & & H & & \\ & & \vert & & \vert & & \vert & & \vert & & \vert & & \vert & & \\ H & - & C & - & C & - & C & - & C & - & C & - & C & = & O \\ & & \vert & & \vert & & \vert & & \vert & & \vert & & & & \\ & & O & & O & & O & & O & & O & & & & \\ & & \vert & & \vert & & \vert & & \vert & & \vert & & & & \\ & & H & & H & & H & & H & & H & & & & \end{array}$$

In the process of muscle action and recovery, this fuel molecule is broken in half, then six molecules of H_2O are stripped off, and the carbon atoms join with oxygen from the lungs to make six molecules of CO_2.

Here is a short general account of living chemistry greatly oversimplified. (Much of this paragraph is drawn from the excellent chapter on biochemistry in Matter and Change by Sir William Dampier (Cambridge, 1924).) The chief food substances--starch, sugars, fats and proteins--have large molecules, built up of smaller molecular complexes which are themselves built up from atoms. In general, the smaller complexes are made by plants and linked in a particular pattern to form plant substances such as starch and cellulose. An animal, whether eating vegetable or animal food, breaks down these substances and rearranges the constituent parts to form the large molecules that it needs, but it does not synthesize such parts itself. It gets energy for movement and other activities by breaking

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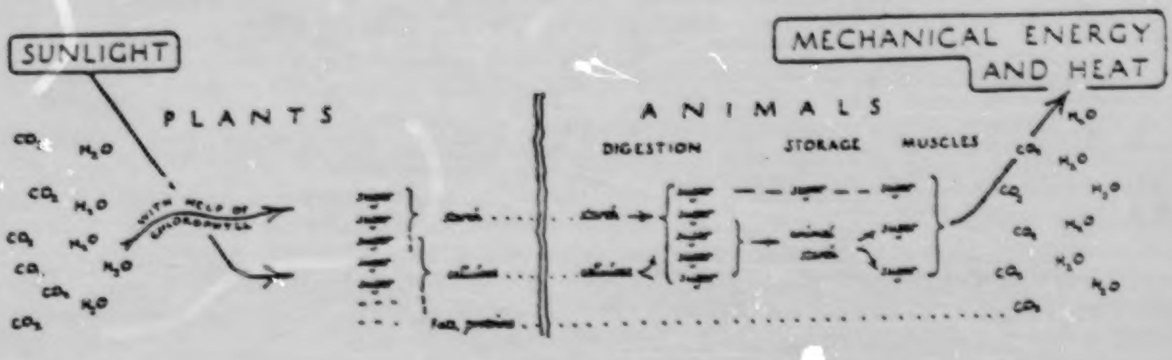

Figure 7

down some of the molecular complexes yet further into carbon dioxide and water. This energy was originally obtained from sunlight by plants and stored in their preliminary syntheses. The linking and unlinking of the small complexes in the animal digestion is usually a simpler affair, not involving the transfer of much energy, and rendered swift by the action of enzymes or organic catalysts. The large molecules in our food are: Starch and cellulose, both of them multiple gangs of simple sugar molecules like dextrose; fats with long CH_2 chains; and proteins, bigger still, very complicated, and essential for building and repairing tissue. The process by which chemical energy is released in warming the body or working its muscles is essentially the same as burning. When fuels burn in a fire, they join with oxygen to form water and carbon dioxide. Simple body fuels such as dextrose sugar join with oxygen from the lungs to form water and carbon dioxide, but the process is gentler and less direct than in a fire: no fiery temperature is produced but the same energy is released. Plants take water and CO_2 from the air and join them together to make the sugars, starch, and cellulose that are the main energy supply for animals.

The animal body gets its fuel for muscles like this: it extracts simple sugar molecules from food--much as a chemical factory extracts fuel alcohol from wood pulp--and keeps them stored in multiple gangs which are insoluble animal starch molecules. These stored starch molecules split up to maintain a supply of sugar. When muscles contract to do jobs, the sugar is converted, in two stages, into water and carbon dioxide. Animals also store fats from their vegetable food to be burned when needed for body heating.

INVESTIGATION 17: ENERGY

Then, what man and animals have undone is re-made by plants, ready for animals to use again. How can plants do this? We cannot make a flame reverse its action; we cannot make a burnt fire "unburn" itself. How can plants do this vital synthesis for us, the latching together of fuel molecules? Since the unlatching releases some chemical energy, the plants must put energy back into the combine. They need both a supply of energy and a mechanism for using it to re-latch H_2O and CO_2 into starch and cellulose. Sunlight provides the energy, packaged in minute chunks of light waves, and the plant provides clever molecules such as green chlorophyll to effect the manufacture. In sunlight, green leaves take in CO_2 and manufacture starch. Thus the plant and animal life of the world combine to provide a cycle, starting with water and carbon dioxide and sunlight and ending with water and carbon dioxide and animal heat and mechanical energy. As with all our machinery that uses coal, oil, wind, or waterfall, animals get all their fuel, which they take in as food, originally from sunlight.

Fatigue

This brings us back to a problem: why do our bodies get tired when we merely hold a large load up in the air? That seems to take food energy though it does not provide any visible gain of gravitational P.E. Careful observations shows that we do not hold the load quite still. The load trembles up and down, our muscles carrying on an incessant twitching. If you clench your jaws and cover your ears, you may hear a dull buzzing from muscular vibration. On each tiny raising of the load, we use some chemical energy in our muscles. On the next tiny fall of the load, the gravitational P.E. is returned, but it does not go back into chemical energy—our fuel chemistry is not reversible. Instead it goes into heat which we waste.

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* Taken from Eric M. Rogers, Physics for the Inquiring Mind, Princeton University Press, Princeton, N.J., 1960, pp. 385-387.

Name__________________________

Section________________________

Introduction

When you grasp a piece of metal with your bare hand, it warms quite quickly. If you hold a piece of wood for the same time, it does not warm as quickly as the metal does. What difference would there be if the piece of metal were heavy and wood were much less heavy? In this investigation, you are going to study the variables that influence the amount of heat, $\triangle Q$, which moves from a warm body to a less warm body.

You already know some important information:

1. When heat enters an object, the temperature of that object increases. For example, when a pan of water is placed on a flame, you know the water's temperature will increase. You also know that when the water is removed from the flame, its temperature goes down.

2. When heat leaves an object, its temperature goes down. In other words, heat entering or leaving an object will cause a change ($\triangle T$) in temperature. ($\triangle T = T_2 - T_1$, where T_1 is the temperature of the object at the beginning of the experiment and where T_2 is the temperature of the object at the end of the experiment.) When heat is entering the object, and $\triangle T$ will be negative when heat is leaving.

   Suppose you had two styrofoam cups, one containing twice as much water as the other, and the same amount of heat, $\triangle Q$, was added to each. Would $\triangle T$ in each cup be the same? In other words, if you put the same amount of heat into samples of the same substance with different masses, how will their temperature changes compare? The following experiment will provide data for you to use to answer that question.

Exploration

Pour 150 cm^3 of the room temperature water into one styrofoam cup (mark it Cup A) and 300 cm^3 into a second cup (mark it Cup B). Record the volume and mass of the water used in each cup in Table I.

1. How will you determine the mass of the water so that you do not include the mass of the cup?

___

___

Record the temperature of the water in each cup at T_1 in Table I.

Your are going to add equal amounts of heat, $\triangle Q$, to each cup using the immersion heater. Doing that safely and accurately is very important. Be sure to follow the following procedure exactly as it is written.

2. Without plugging in the immersion heater, place it into a container of room temperature water (not Cup A or B). What does this accomplish?

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___

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3. Remove the heater from the room temperature water and place it into Cup A. Plug in the heater and let it heat the water for exactly one minute. Stir the water with the heater while heating.

4. After one minute of heating, unplug the heater, put a thermometer into the water and gently stir the water with the thermometer, and begin recording the temperature of the water in Cup A every 10 seconds until the temperature starts to decline or remains the same through five consecutive temperature measurements. Read the thermometer to the nearest tenth of a degree. Record the highest temperature as T_2 in Table I.

5. Now repeat Steps Two through Four using the water in Cup B and record the values in Table I. Be sure to keep the immersion heater at the same level in the liquid as you did in Cup A. Why should you do this?

6. If you followed Steps Two through Five for Cups A and B, you have added equal amounts of heat, ΔQ, to each cup. Explain why that is true.

Stated in an equation, $(\Delta Q)_A = (\Delta Q)_B$. Do not proceed until you understand why this equation is correct.

Table I

	Cup A	Cup B
Volume of water, ____ cm^3		
Mass of water, ____ g		
T_1, ____ °C		
T_2, ____ °C		
ΔT, ____ °C		

Name________________________

Section______________________

The Idea

1. Compare the temperature changes of the water in the styrofoam cups. How do $(\triangle T)_A$ and $(\triangle T)_B$ compare?

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2. Based on the data you have just taken, what effect does the mass of a substance have on its $\triangle T$ when the same $\triangle Q$ is added? (Write a complete sentence which gives an answer to that question.) Be sure to use evidence provided by the experiment you just completed.

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3. Write an equation that expresses how the variable $\triangle T$ is related to the variables $\triangle Q$ and mass, m, of the water to which $\triangle Q$ is added.

$\triangle T=$__________________

4. Now rearrange your equation to solve for $\triangle Q$.

$\triangle Q=$__________________

5. What will be the units of $\triangle Q$?

____

6. How much heat is transferred into water when one gram of water increases in temperature by 1°C?

____

When you are referring to 1 g°C of heat added to WATER, you can give that amount of heat the name CALORIE. Therefore, the units of heat transferred into or out of WATER are calories.

7. Write the definition of a calorie. One calorie is:

____

____

8. How many calories of heat were transferred into the water in Cup A?

____CALORIES

9. How many calories of heat were transferred into the water in Cup B?

____CALORIES

Name________________________

Section______________________

Expansion of the Idea

Part 1: An Experiment

Follow the same procedure you used to find the $\triangle T$ in water. Use the same immersion heater you used in the first part. Use 150 grams of each of the liquids labeled #2 and #3 and record your data in Table II. Let water be Liquid #1 and use the data you collected from Cup A of the Exploration section of this experiment.

1. How will you measure the masses of Liquids #2 and #3 so that you do not include the mass of the cup in your measurement? Write the method you will use.

Proceed with the experiment. Remember to keep the heater coils submerged to the same level while heating as in the Exploration section. Record your data in Table II.

Table II

	Liquid #1 (water)	Liquid #2	Liquid #3
T_1, ____ °C			
T_2, ____ °C			
$\triangle T$, ____ °C			
mass, ____ g			
$m\triangle T$, ____ g°C			

When you finish with Liquids #2 and #3, pour them into the containers marked Used Liquid #2 and Used Liquid #3, respectively. Rinse and clean your styrofoam cup between trials and after you finish this part of the experiment.

2. How do the values for $m\Delta T$ for liquids #2 and #3 compare with $m\Delta T$ for water?

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3. What do you conclude about the value of $m\Delta T$ for any substance when the same amount of heat is added to it as was added to these two liquids?

____

____

4. Which variable(s) would you suggest as being the most likely responsible for the differences in $m\Delta T$?

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Name______________________

Section______________________

Expansion of the Idea

Part 2: Problems

1. Suppose you heat 200 g of water beginning at 20° C in a small beaker and 1000 g of water beginning at 20° C in a large beaker until both have reached a temperature of 50° C.

   a. How much heat, in calories, has been added to the contents of each beaker?

   ____

   b. Compare the amounts of heat that have been added to the beakers.

   ____

   ____

   c. How can you explain why more heat was added to one beaker even though the temperature change was the same?

   ____

   ____

2. The soldiers defending castles in the Middle Ages poured hot oil rather than hot water onto attacking soldiers who were attempting to climb the walls. Why would hot oil be more suited for this purpose? Remember that water boils at 100° C and animal fats and oil begins decomposing at about 200° C (they do not boil).

   ____

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   ____

3. Which liquid, water or glycerine, would be best to use in a hot water bottle? The purpose of a hot water bottle is to transfer as much heat to the human body as possible with the least temperature change of the liquid.

Name________________________

Section_______________________

Expansion of the Idea

Part 3: Readings Questions

1. In Thompson's work with the boring cannon, what caused the temperature of the water in the box to increase from 60° F to 212° F?

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2. In your own words, define mechanical equivalent of heat. Include the numerical measures in your answer.

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3. Of what value was Thompson's work in the historical hierarchy of work with heat?

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4. Mayer was credited with establishing the Law of Conservation of Energy. One might propose, however, that Thompson had already established the law through his work with the boring cannon. How would you defend this position?

5. Explain the reasoning behind the assumption that heat is a form of energy.

6. Consider the following story:

"A young man in the forest spies an apple tree. He picks an apple from the tree and begins eating it. Then he reaches into his pocket, takes out a box of matches, and strikes a match against the box. The boy places the lighted match near a piece of paper to start a pile of wood (he had previously gathered) burning. Over the fire he places a pail of cool water he wants to heat for coffee. Soon the water in the pail begins to boil."

Determine the energy chain (that is, energy transfer: energy forms) involved in this story beginning with the apple tree and ending with the pail of boiling water.

READING: THE MECHANICAL EQUIVALENT OF HEAT*

Benjamin Thompson was born in Massachusetts in 1750 and grew up there. He did not have much formal education. During the revolutionary period in this country, Thompson's sympathies were with England and he moved to that country. He later went to Bavaria and became an assistant to the Duke of Bavaria. It was during this period that Thompson made important discoveries on the nature of heat. (He also invented the pressure cooker and the drip coffee maker.) For those discoveries, Bavaria awarded him the title of Count Rumford.

Thompson's scientific curiosity was stimulated by the innumerable attempts to explain and countless experiments to track down the nature of heat. In spite of years of speculation and experimentation, heat was still nothing more than a word, caloric. Caloric was conceived of as a mobile fluid which was present in varying amounts in the pores of all bodies. Caloric could be squeezed out of such bodies in the form of heat, or added to them by the agency of flames. Observation showed that objects expanded when heated and that metals increased in weight when burned. Such data seemed to add weight to the theory, and the theory of caloric prevailed for more than a century.

The question as to whether caloric actually possessed weight was studied by Hermann Boerhaave of Leyden in 1732. He made careful determinations of the weight of a five-pound mass of iron both before and after heating it to a red heat, but reported no change in weight. Buffon in 1775 weighed a fifty-pound mass of iron while white hot. Then, after cooling it to the freezing point of water, he weighed it again and insisted that the iron suffered a loss of weight of nearly two ounces. The following year John Roebuck, an English scientist, repeated these experiments using both gold and iron. His results were contradictory. Sometimes he obtained an increase in weight; at other times, the balance showed no change at all, and some of his reading even showed a loss of weight.

INVESTIGATION 18: MEASURING HEAT

Was caloric really material? No one had as yet satisfied stubborn men of science on this question. Thompson saw obvious errors in the procedures of the other scientists who had attempted to clear up the matter of caloric. He planned to avoid these pitfalls and worked out a series of beautifully controlled experiments. He took two identical thin glass flasks, one of which he filled with carefully distilled water and the other with a dilute alcohol solution. The flasks were then sealed and hung, one from each arm of a very sensitive balance in perfect equilibrium. The temperature of the room in which the balance was placed was regulated at exactly 61° Fahrenheit. The apparatus was then moved into another room where the temperature was regulated to remain at 29° Fahrenheit, three degrees below the freezing point of water.

At the end of forty-eight hours, the water in the first flask was frozen solid. The solution of alcohol, which has a freezing point lower than 29° Fahrenheit, remained liquid. Thompson also noted that the equilibrium of the balance had been disturbed and that as much as 0.134 grains of metal has to be attached to the side of the balance carrying the pure water before this equilibrium could be re-established. This disturbance apparently pointed to the conclusion that some caloric had leaked out of the flask containing the water. But to check the accuracy of this conclusion he removed the added grains of metal and carefully returned the whole apparatus to the room where the temperature remained at 61° Fahrenheit. The ice in the flask thawed out; the balance returned to its original equilibrium. Apparently the lost weight had been recovered without adding anything material to the flask. Confusion was worse confounded. Thompson checked the balance and the apparatus once more and could find no change.

One of the industries in Europe during the days of Thompson was cannon boring. The middle of a huge cylindrical piece of metal was actually removed by the boiling process. In 1797 Thompson arranged to have an unfinished solid cannon, a gun metal six-pounder ready for boring, rotated against a steel borer. He devised a method of measuring the amount of heat liberated during this operation. The cylindrical mass of metal was placed in a wooden box holding 18 3/4 pounds of water. By means of several teams of horses, the cannon was rotated against the steel cutting tool. At the end of 2 3/4 hours of boring, the heat liberated raised the initial temperature of the water from 60° Fahrenheit to 212° Fahrenheit, and the water began to boil. This was indeed a spectacle even for Thompson. "It would be difficult," he wrote, "to describe the surprise and astonishment expressed in the countenances of the bystanders on seeing so large a quantity of water heated, and actually made to boil, without any fire."

Thompson began to feel more certain now that the heat generated was the result of mechanical action only. But where did the heat really come from? How could he pin down the answer to this question? Could the heat have come from the action of the oxygen of air combining with the metal of the cannon? That was impossible, since the cannon was under water. Was the heat which was generated inexhaustible? That he could find out by means of another experiment. He repeated the boring process. More water kept boiling off. Apparently the heat was inexhaustible. The experimenter wrote in conclusion, "It is hardly necessary to add that anything which any insulated body, or system of bodies, can continue to furnish without limitation cannot possibly be a material substance. It appears to me to be extremely difficult, if not quite impossible, to form any distinct idea of anything capable of being excited and communicated in these experiments except it be motion."

Thompson next wanted to learn just how much heat was liberated during a boring operation and devised experiments to find out. Using wax candles of 3/4 inch diameter he showed that "the quantity of heat produced by the boring (of a weighed quantity of metal) was greater than that produced by the continuous burning of nine such candles."

His next step was a bold and fundamental one. He attempted to discover the exact relationship between the exact amount of energy employed in the boring operation and the exact amount of heat generated during the boring process. Thompson's work led him to conclude that a direct proportion existed between the work (W) done in cannon boring and the amount of heat (Q) generated. That proportion can be stated as $Q \propto W$. Thompson next assigned himself the task of determining how to turn that proportionality into an equality. After much experimentation, he arrived at the figure that 847 foot pounds of work produced one British Thermal Unit of heat (Btu).

(A Btu is the amount of heat needed to raise the temperature of one pound of water one degree Fahrenheit.) About forty years later, in 1842, the German scientist Julius R. Mayer employed a different experiment to establish the principle of the conservation of energy, one of the most significant determinations in the whole history of science. He measured the heat developed during the compression of air and showed that heat and mechanical energy are mutually convertible. Unfortunately, the work of this overshadowed genius was neglected by the world of science. At about the same time, James Prescott Joule performed similar experiments which proved conclusively that the mechanical equivalent of heat is equal to 780 foot-pounds. (The figure accepted today is 778 foot-pounds.) Joule arrived at his value in an interesting manner. As a young man he was fascinated by electric motors. In those days electric motors were as new and full of possibilities as rockets and satellites are today. He noticed that an electric current produced heat. He knew how to compute the electrical energy (work) in ft·lb, and he compared this with the number of Btu's of heat produced. Then he discovered that he could heat water by stirring it with a paddle wheel. When he compared the work done by the wheel with the number of Btu's produced, he found that the result agreed fairly well with that from the electricity experiment. Joule spent years of his life heating all sorts of things and measuring the amount of work required to produce 1 Btu of heat. Each time he found that it took about 780 ft·lb per Btu.

Why was Joule excited about this and why did it excite other people? Thompson, too, had thought that heat was energy instead of a fluid because the more work the men did in boring the cannon, the more heat was produced. However, his observations lacked exact measurement. This is what Joule provided. He showed that no matter how the work was done, by stirring paddle wheels, by an electric current, or by any one of many other methods, whenever a certain amount of work was done, the heat produced was 1 Btu.

Joule had transformed Thompson's proportionality, $Q \propto W$, into an equality, $W=KQ$, where K is equal to 778 foot-pounds per Btu. That equation is a statement of the First Law of Thermodynamics. The constant K is called the Mechanical Equivalent of Heat and literally means the amount of work required to produce one unit of heat. In the

INVESTIGATION 18: MEASURING HEAT

English system of measurement k=778 ft·lb/Btu and in the metric system k=4.18 joules/calorie.

* Taken from Jaffe, Bernard, Men of Science of America (New York, Simon and Schuster, 1958), pp 61-65. Used with permission.

INVESTIGATION 18: MEASURING HEAT

READING: CONSERVATION OF ENERGY*

Heat Flow

The dissipation of mechanical energy through frictional forces is not the only method of increasing the temperature of an object. You can warm your hands either by rubbing them together or by dipping them into hot water. When they are in hot water, there is a transfer of energy from the more lively random molecular motions to your cold skin. When such a transfer of thermal energy from a hotter to a colder body occurs, we say that heat flows from the first to the second body.

We can trace a given amount of energy from gross mechanical energy into internal thermal energy of a given sample through either of two routes. The energy in the sample or it may be converted to thermal energy elsewhere and reach the sample by heat flow. By experiment we can show that the method of transfer does not matter. The same amount of thermal energy winds up in the sample either way.

Suppose that we have two containers, one containing a certain amount of water, as in the Joule experiment, and the other a different amount of another liquid, such as oil. We perform the Joule experiment described in the last section separately on each liquid; and, we find that it takes x joules of work to raise the temperature of the oil one degree. Now we start again with the water and oil at their original common temperature. We churn the water along until we have dissipated (x+y) joules of mechanical work. The temperature of the water rises more than one degree. Then we place the container of oil in contact with the container holding the water. We keep the whole system insulated. The temperature of the oil rises and that of the water drops. Finally equilibrium is reached: the temperature of both liquids becomes the same and remains constant. We measure the final temperature of the water and oil, and we find that each is one degree higher than it was at the start.

We conclude the following: of the (x+y) joules of work done on the water, y joules have been transferred to the oil by heat flow. We make this conclusion because we know that exactly y joules of work are necessary to produce a temperature rise of one degree in the oil. The remaining x joules have produced the one-degree temperature rise of the water. Thus we have shown that the work necessary to produce a definite temperature rise in a given liquid is the same whether the energy is transferred to the liquid by heat flow or whether the mechanical energy is dissipated directly in the liquid.

Quantitative Relation of Energy Dissipation and Temperature Rise

Let us be specific about the energy that must be dissipated to raise the temperature of a gram of water by 1° C. If we dissipate mechanical energy, we find that we must transfer 4.2 joules. Alternatively, we can put the energy in by heat flow from hot oil by a Joule experiment. Then we find that the oil must lose 4.2 joules by heat flow to warm the water. Whichever way they are received, 4.2 joules of energy will raise the temperature of the water just the same amount.

We can combine the two ways of heating up a mass of material. Suppose we have a gram of water surrounded by a bath of hot oil, all insulated from the rest of the world, and with a little insulating shaft leading to paddles in the water. Now we dissipate one joule of mechanical energy in the gram of water by whirling the paddles; we also allow 3.2 joules to flow into the water from the oil as indicated by the fall in temperature of the surrounding oil bath. We then find that the total transfer into increased internal energy of the gram of water is 4.2 joules. This is indicated by a 1° C rise in temperature, the same rise in temperature that occurs if we let 4.2 joules flow into a gram of water purely by heat flow or dissipate it by mechanical means alone. In general, the transfer into internal energy is given by

$$\Delta W + \Delta Q,$$

the sum of the transfer ΔW by mechanical energy dissipation and the transfer ΔQ by heat flow. This total transfer has the same effect no matter what fraction of it is ΔQ.

We can dissipate energy in water in innumerable ways--even dropping stones into it will do. The result is always the same. Whenever 4.2 joules are dissipated in a gram of water, its temperature rises 1° C. To raise the temperature of 2 grams takes just twice the energy. Similarly, whenever 12.4 joules are dissipated in a mole of helium (4 grams), its temperature rises 1° C. The rise in temperature is different for different substances as the examples show, but in any one substance, we always get the same results over the same temperature range.

Precise measurements show that 4.185 joules are necessary to raise the temperature of 1 gram of water one degree from 14.5° C to 15.5° C. This amount of energy is a calorie. (Units like the calorie came into use for measuring heat even before heat was agreed to be a form of energy. They are used because it is so easy to estimate a quantity of heat by giving it to a known mass of water and measuring the temperature rise. Note that there is a larger unit, the Kilocalorie or Calorie with a capital C, which is 1000 times as big as the small c calories. The Calorie is the unit commonly used today in specifying energy yields from food.) The calorie is just another unit of energy. We could measure the kinetic energy of the bulk motion of an object in calories just as well as in joules; for instance, a 3 kg mass moving 2 m/sec has $1/2(3)(2)^2=6$ joules or (6)/4.185 1.45 calories of kinetic energy; however, the joule connects directly without units of force and distance so that the joule is usually more convenient. We shall stick to joules. One unit is enough.

Conservation of Energy

When gross mechanical energy is changed into heat, the same number of joules of mechanical energy gives the same heating. If we put the heat into a standard amount of water, for instance, we always get the same temperature rise. But Joule experiments and heat-flow experiments fail to answer all the questions we can ask about heat and mechanical energy. Can we turn heat into mechanical energy at the same rate of exchange at which the mechanical energy turns into heat? Can we get 4.2 joules of gross mechanical energy from the heat that comes out of a gram of water when its temperature falls 1° C? Our earlier experiments suggest that we should get 4.2 joules, but we need direct evidence. Lots of things--even door latches--act one way when going in one direction and differently when reversed.

INVESTIGATION 18: MEASURING HEAT

The simple way to check up on the change from heat to mechanical energy would be to pour a known amount of heat $\triangle Q$ into a heat engine and measure the work $\triangle W$ the engine does. We must be sure, however, to leave the heat engine at the end with the same energy it had at the beginning; otherwise we must know how much extra energy the engine has retained or how much it has given us from its original stock.

The usual way to make sure that the engine is not contributing energy is to get the engine back at the end into exactly the same condition it was in the beginning. We then find, however, that the engine does not simply take in the heat $\triangle Q$ and produce work. It takes in the heat $\triangle Q$, produces some work, and pours out some heat. (It is to get rid of that rejected heat which must be poured out that cars and all other heat engines have radiators.) If we wish to see whether thermal energy can be turned into gross mechanical energy joule for joule, we must use the net flow of heat--that going in minus that coming out--to compare with the work. Consequently, we must measure all the heat taken in and all the heat coming out by observing the temperature changes of the surroundings. Then we can compare the net flow of heat into the engine with the net work measured by forces times distances. Such experiments have been carried out. The Frenchman Hirn even chased all the heat and all the work in and out of the steam engine of a textile mill. The result is that the heat does turn into mechanical work at par. When we can change 4.2 joules of heat into mechanical energy, we get 4.2 joules of mechanical energy.

Although the energy equivalence of heat and mechanical energy is complete--the same when the transfer is in either direction--there is an essential difference between transfers in the two directions. We can easily change all of a supply of gross mechanical energy into heat; but we can normally change only a fraction of the heat available into gross mechanical energy. We pour the heat into an engine at a high temperature; some of it must be poured out again at a lower temperature; and the remainder turns into mechanical energy at full value. The fact that whatever energy is changed in form is converted at full value is a version of the first law of thermodynamics. The question of how large a fraction can be converted is the subject of the second law of thermodynamics.

INVESTIGATION 18: MEASURING HEAT

We now believe that heat and mechanical energy are just two different forms of energy, and no energy is lost or gained in turning one into the other. Energy, like momentum, is conserved; but to see that it does not change amount, we have had to find measures of heat and keep track of the amount that is locked up in internal energies as well as the energy of bulk motions and raised weights. No single experiment leads all by itself to our conviction that energy is conserved. But we assume conservation in thinking about all kinds of physical and chemical processes. Innumerable such processes go on daily: chemicals react, heat is released, engines run. And energy bookkeeping balances out time after time. If any substantial amount of energy were disappearing, we should have felt the loss long since. If there were mysterious sources from which energy entered, the gain should have become apparent. It is on this overall check of conservation as well as on innumerable detailed checks of all sorts of transformations that our belief in energy conservation really rests.

By adding heat flow to mechanical work, we have extended the conservation of energy beyond simple mechanical systems. The extension was made by including a new transfer mechanism. Heat flow was the first new mechanism to be added to work, but we have since discovered that other mechanisms have to be included. For example, the energy reaching us from the sun does not arrive here either through mechanical work or through the kind of heat flow that occurs between a hot and a cold body in contact. Radiation--visible and invisible light--carries the energy. If we want the conservation of energy to span our universe, we must take account of this energy of radiation in the same way that we had to include the momentum of radiation to explain the behavior of bodies which emit or absorb light.

Experiment and theory combine to assure us that energy is indeed conserved when radiation is included. But, whereas the transfer of thermal energy by ordinary heat flow can be viewed as a microscopic version of the transfer of energy through work, the transfer through radiation is different. We cannot be satisfied that we understand that mechanism until we have studied radiation. Here we shall not try to go through the details. Even without studying the mechanism, however, we can extend the conservation of energy to include radiation by performing experiments like those with which we extended the conservation of energy to include heat flow. We can use a measured amount of energy to run a light for a while and absorb the emitted radiation on a black surface and the energy left as heat in the source of light. We find the sum is equal to the energy we fed in. Part of the energy has gone from the light source to the absorber. And it has gone without loss or gain.

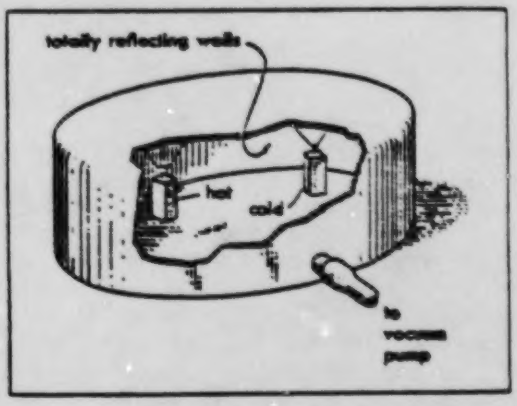

Figure 1. A hot object and a cold object are placed in a container with reflecting walls. There is a good vacuum in the container, so that energy is not transferred by the air molecules. Even so, the warm body cools off and the cold body warms up as energy is transformed by radiation.

The radiation need not be visible. For example, we can put a hot body and a cold body inside of a very good reflector of radiation (Figure 1). We make such a good vacuum inside the reflector that ordinary heat flow cannot take place. Nevertheless, the hot body loses energy and the cold one gains energy. The energy flows from one to the other as radiation. We find the total energy is conserved.

Like the transfer of momentum, the transfer of energy by radiation takes time. The light from the sun transfers its energy and momentum to us here 8.3 minutes after it leaves the sun. As far as we know, nothing ever moves faster. Energy transfer by other mechanisms is slower, but usually the distances are so short that we may fail to detect the time lag.

INVESTIGATION 18: MEASURING HEAT

For many ordinary mechanical systems--such as billiard balls colliding or the earth going around the sun or even the operation of a steam engine--the part played by radiation in energy transfer is so small that we can usually ignore it. But radiation must be considered not only when we look into the energy transfer from stars but also whenever we consider atoms emitting or absorbing light.

All physical happenings, from the evolution of a star to the life of a firefly, are in essence transformations of energy from one form to the other. Even on a cosmic scale, we can trace its flow. Physicists have now learned about the nuclear energy that supplies the radiant energy of the stars. Our physical knowledge is consistent with a universal conservation of energy. To the best of our knowledge, the total energy in a region changes only when an exchange of energy occurs between the region and its surroundings. Then, if our region is the whole universe, we can expect no change of the total energy--because, by definition, there is nothing outside the universe. This assumption, that the total energy of the universe is constant, is the basis of most cosmological theories. But that is a daring generalization from our limited experience. We live in a small corner of the universe, and we have tested the validity of our physical laws over a very limited period of time. It is conceivable that these laws, including the law of conservation of energy, are not rigorously correct. In our limited view, energy is conserved with great precision; but a tiny rate of destruction or creation may have escaped our notice--if, for example, the total energy of the universe had doubled in the course of several billion years, we probably should not be aware of this change. Indeed, some cosmological theories assume a continuous creation of energy.

Here is one of the live scientific questions of today. Cosmologists are working hard to find out whether energy is completely conserved over the whole universe. And just now, for the first time, there is a possibility of actual experiments to decide between the rival theories.

* Physical Science Committee, Physics, (Boston: Heath, 1960), pp. 434-437. (Used with permission of the author and publisher.)

INVESTIGATION 19: MEASURING HEAT IN SOLIDS STUDENT GUIDE

Name ____________________

Section ____________________

Introduction

In your work with heat so far, what have you assumed about the relationship between the amount of heat ($\triangle Q$) generated by the electricity in the immersion heater and the amount of heat ($\triangle Q$) absorbed by the liquids?

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In this experiment, you will be working with hot metal cylinders rather than immersion heaters. You will be transferring heat from the hot cylinders to water in a styrofoam cup. How would you expect the heat ($\triangle Q$) given off by the hot cylinders to compare with the heat ($\triangle Q$) absorbed by the water in which the cylinder is immersed?

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Exploration

Attach about 40 cms of string to each cylinder. Record the type of metal from which the cylinder used is made in the space at the tops of the columns in Table I. Proceed with the following instructions. Be certain you do everything exactly as the instructions tell you.

1. Put one of the cylinders gently into the container of boiling water letting the string hang over the edge of the container. Leave it in the boiling water for at least three minutes. While the cylinder is being heated to the temperature of boiling water, you can be working on Step 2.
2. Put 300 g of room temperature (or tap) water into a styrofoam cup. Record the temperature of the water as T_1, making certain the liquid level in the thermometer has stopped changing when you read it. Record T_1 in Table I.

3. Record the temperature of the boiling water as T_1 of the cylinder. Assume that the cylinder will have the same temperature as the boiling water when you transfer it to the water in the styrofoam cup. Why is that assumption reasonable?

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Transfer your thermometer from the boiling water back to the styrofoam cup of room temperature water; recheck the water temperature there.

4. When you are sure that the cylinder has been in the boiling water at least three minutes, bring your styrofoam cup next to (but not touching) the container of boiling water. Quickly transfer one cylinder from the boiling water to the water in the styrofoam cup. Set the cup on a laboratory table, begin stirring, and record the temperature of the water in the cup every ten seconds until the temperature stops rising and begins falling again, or until the same temperature, to the nearest tenth of a cegree, is recorded five successive times. Be sure to record the temperature to the nearest tenth of a degree in Table I at T_2, the final temperature of the water in the cup.

5. What is happening to the temperature of the cylinder while it is in the cup?

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6. What will be the temperature of the cylinder when the temperature of the water in the cup stops rising?

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Record the final temperature of the cylinder as T_2 in Table I.

a. Dry the cylinder. Find its mass in grams to the nearest tenth of a gram. Record its mass in Table I. Also record the substance of which the cylinder is made.

b. Repeat steps 1 through 5 for each of the other cylinders.

c. Find $M\Delta T$ for the water in the cup and for each cylinder and record your values in Table I.

7. Describe what your data show regarding whether or not the heat ($m\Delta T$) lost by each cylinuer is equal to the heat (ΔT) gained by the water.

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Check with other groups to find out if they have data similar to yours.

Table I

Substance	CYLINDER			
Mass, g				
T_1, °C				
T_2, °C				
ΔT, °C				
	WATER			
Mass, g				
T_1, °C				
T_2, °C				
ΔT, °C				

8. Write a summary of the data in Table I and discuss that summary with the class and your teacher.

INVESTIGATION 19: MEASURING HEAT IN SOLIDS STUDENT GUIDE

The Idea

Use the information from Table I to complete Table II. Be sure to include the names of the several metals used.

Table II

Cylinder ($m\Delta t$)		Water ($m\Delta t$)
Substance	Heat Lost	Heat Gained

1. The data in Table II show that the heat lost by each metal is not equal to the heat gained by the water. What did you find at the end of Investigation 18 that was similar?

2. Which of the variables in Investigation 18 did you decide was primarily responsible for what you found?

3. What variable do you believe is responsible for heat lost not equaling heat gained in Table II?

INVESTIGATION 19: MEASURING HEAT IN SOLIDS STUDENT GUIDE

Name______________________

Section_____________________

Expansion of the Idea

Part 1: A Derivation

You know that $(m\triangle t)$ metal$\neq(m\triangle t)H_2O$. That means that heat lost by the metal is not equal to the heat gained by the water. But the Law of Conservation of Energy says it must!

1. How can you use the specific heat capacities(C) of the metal and water to adjust the foregoing equation so it is an equality?

2. Write your new equation for $\triangle Q$.

3. Solve the equation for C and calculate its units.

4. The specific heat capacity of water is 1

5. Calculate the specific heat capacities of the metals you used in this investigation and record the values in Table III. What equation are you going to use to determine these values?

Table III

Substance	Specific Heat Capacity

Name______________________________

Section____________________________

Expansion of the Idea

Part 2: Specific Heat

Frequently in physics, specific heat is used instead of specific heat capacity. Specific heat is the ratio of the specific heat capacity of a substance to the specific heat capacity of water.

Write the equation for specific heat.

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What are the units of specific heat? Explain your answer.

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Calculate the specific heats of the metals you used in this investigation and record the values in Table IV.

Table IV

Substance	Specific Heat

How do the specific heats you calculated for Table IV compare with the specific heat capacities you found in Table III?

How would you explain the relationship between specific heat and specific heat capacity?

INVESTIGATION 19: MEASURING HEAT IN SOLIDS   STUDENT GUIDE

Name__________________________

Section________________________

Expansion of the Idea

Part 3: Problems

1. A 20 kg mass of water, originally at 90°C, loses 1600 kcal of heat. What is its final temperature?

2. The temperature of 200 g of water dropped from 80°C to 20°C when it was left in a room. How much heat did the water lose?

3. One hundred grams of water at 50°C are mixed with 200 g of water at 5°C. The temperature of the mixture stops changing at 20°C.

   a. How much heat did the cold water gain?

   b. How much heat did the hot water lose?

4. A bathtub contains 1.5×10^2 kg of water at 20°C. How much water at 65°C must be added to provide a hot bath at 40°C?

5. How hot must a 100 g iron bolt be to make 200 g of water at 20°C reach the boiling temperature of 100°C? (C_{Fe}=0.11 cal/g°C)

6. The mass of a block of metal is 0.50 kg. To raise its temperature from 20°C to 60° requires 1.86 Kilocalories of heat. Find the specific heat of the metal.

7. A piece of hot glass was taken from a pot of boiling water ($T=100^{\circ}C$). The piece of glass was put into an aluminum ($C=0.214$ cal/g°C) pail which contained 100 g of water. The aluminum pail had a mass of 500 g. The specific heat capacity of the glass was 0.32 cal/g°C. The initial temperature of the water was 25°C; the final temperature was 30°C. What was the mass of the piece of glass? (Assume that no heat dissipates from the pail to the air.)

8. A block of aluminum ($C_{Al}=.22$ kcal/kg°C) is rubbed along a bar of aluminum 1860 times. The force of friction between them is 45 N. The block is moved 10 cm each time. The total mass of the aluminum is 0.4 kg. The initial temperature of the metal is 10°C. Assume all heat stays in the metal.

   a. Find the work done.

   b. Find the amount of heat produced.

   c. Find the final temperature of the metal.

INVESTIGATION 19: MEASURING HEAT IN SOLIDS STUDENT GUIDE

Name________________________

Section______________________

Expansion of the Idea

Part 4: Reading Questions

1. Why is snow a better insulator than ice?

2. Why does a thick layer of material transfer heat more evenly than a thin layer of material?

3. Why does a piece of aluminum metal $(T=25^{\circ}C)$ feel colder than a piece of wood $(T=25^{\circ}C)$?

4. You come in from a very hot day. You go to the freezer and pull out a tray of icecubes. The heat has blistered your brain and you uncontrollably lick the icecube tray. Your tongue sticks to the tray. Suddenly, someone knocks at the front door. Why did your tongue stick to the tray? How are you going to get away to answer the door?

5. In coastal areas the winds blow landward during the day and seaward during the night. Using your knowledge of specific heat capacity and convection currents, explain this phenomenom.

INVESTIGATION 19: MEASURING HEAT IN SOLIDS

READING: CONDUCTION AND CONVECTION--A HEATED EXCHANGE

If you place a metal spoon in a cup of hot chocolate, you might notice that the handle of the spoon becomes warm even though it is not touching the chocolate. If you were outside on a winter morning, you might think that a wooden surface was warmer than a metal surface. How would you explain these phenomena? Physicists use the term CONDUCTION to explain them.

You may remember from chemistry that as molecules are heated, they begin to move faster. The faster they move the more likely it is that the molecules will collide with one another. If one molecule strikes another, it exerts a force on that molecule. You know that the result of a force acting on a mass is an acceleration of that mass. Thus, the molecule that is struck moves faster and collides with other molecules. The attacking molecule will be decelerated. The result of this increased molecular motion is an increase in the temperature of the substance. This transfer of heat by molecular contact is called conduction.

Let's return to our example of the spoon in the cup of hot chocolate before the idea gets cold. No one has seen a molecule, but there is a model of how heat affects molecules that will help explain why the spoon handle gets hot. That model says that molecules are constantly in motion and that adding heat accelerates them. In the hot chocolate, therefore, the molecules of the liquid are dashing madly about. These molecules would be striking each other, the sides of the cup, and the part of the spoon submerged in the liquid. As the hot chocolate molecules hit the spoon, the molecules in the spoon would move faster and collide with each other. This molecular activity would move up the handle. The result would be an increase in the temperature of the spoon handle. Because of the slowed movement of the molecules of the liquid as they hit the spoon, the hot chocolate would have a decrease in temperature. You should be able to explain why the cup gets warmer.

INVESTIGATION 19: MEASURING HEAT IN SOLIDS

If you had a wooden spoon in the hot chocolate instead of a metal spoon, would the handle of the spoon feel as warm after, say, five minutes? Most of you will agree that the wooden spoon would not get as hot as fast as the metal spoon. How can we explain this difference? You know tbat different substances have different atomic structures, thus, their molecular compositions differ. Some materials conduct heat slowly--these are poor conductors. Poor conductors of heat are good heat insulators. We could say, then, that the metal of the spoon was a good conductor (or a poor insulator) and that the wood is a poor conductor (good insulator).

How can we determine how much heat a certain substance conducts? The quantity of heat a substance conducts is directly proportional to the time involved, the cross-sectional area of the conductor, and the temperature difference between the two surfaces of the conductor, and is inversely proportional to the distance between the two surfaces. In equation form this would be $(\triangle Q=KtA\triangle T)/L$ where K is a constant of proportionality called the thermal conductivity coefficient of the material. The chart which follows lists several materials, ranking them from those with the highest thermal conductivity to those with lowest thermal conductivity.

Table 1

Material	Coefficient (K=cal/sec cm C°)
Silver	1.01
Copper	0.92
Gold	0.70
Aluminum	0.50
Brass	0.26
Cast Iron	0.11
Rock	0.004
Ice	0.004
Window Glass	0.0025
Brick	0.0015
Water	0.0014
Asbestos Paper	0.0006
Snow, compact	0.0005
Wood, fir	0.0003-0.00009
Air	0.00006

INVESTIGATION 19: MEASURING HEAT IN SOLIDS

As you will note, water and air are very poor conductors of heat. This fact will help you understand the function of double-pane windows and doors. The layer of air between the two sheets of glass helps to slow down the transfer of heat from inside the house to the outside (and vice versa). Also, fabrics and materials which have many air spaces serve as good insulators (for example, wool and styrofoam).

If you lighted a candle, how would the flame orient itself? If you held the candle in a horizontal position how would the flame orient itself? The flame is always positioned in an upright fashion. To help us understand this event, let's consider a stove burner. If you placed your hand above a source of heat, you would feel a current of warm air rising from it. The burner heats the air touching it which results in an increase in the speed of the molecules of air. As the molecules move faster, they move farther apart and the air becomes less dense. This warmed air then rises; cool air moves in to take its place. A current of air results. This transfer of heat by currents in a heated gas or liquid is called CONVECTON. The candle flame then is upright due to the convection currents that surround it. The convection process also occurs when liquids are heated. The molecules move farther apart which makes a specific portion of the warm liquid become less heavy. That warm portion rises to the top and cold liquid moves in to take its place.

Winds are caused by convection processes. The sun heats the earth, the warm air rises and is displaced by cooler air. You might expect all winds in the northern hemisphere to be southerly (and northerly in the southern hemisphere) as the equatorial region would heat up more than the polar region. However, other factors such as the change of seasons, mountain masses, bodies of water, the rotation of the earth, etc. affect wind currents.

Conduction is the transfer of heat due to molecular collisions. As the molecules collide and interact with each other, the material usually expands slightly. Heat, for example can be used to help remove a metal cover from a glass jar. The metal expands more than the glass. The amount that an object will expand by molecular collisions, therefore, depends upon the material it is made of.

Convection also depends upon the collision of molecules with each other and other objects. There is, however, a basic difference between convection and conduction. In convection, the space each molecule clears by colliding with others causes the gas or liquid to expand a great deal. The lesser number of molecules occupies the same space that a larger number occupied before heating. In other words, the density becomes less. That causes a set volume of the gas or liquid to weigh less after heating and that volume rises (as is evidenced when warm air rises).

INVESTIGATION 20: CIRCUITS AND CURRENTS STUDENT GUIDE

Name______________________

Section____________________

Introduction

This investigation is the first opportunity you have had to study electricity. You have used electricity all your life but perhaps you have not had the opportunity to consider where it comes from and why it is useful. The next few investigations will involve you in thinking about and using electricity.

You already have some important information about electricity. You know that electric motors are used in electric appliances such as mixers, vacuum cleaners, lawn mowers, pumps, drills, sanders, and saws. Each of those appliances exert a force over a distance. Describe how each of these exerts a force over a distance.

1. Electric mixer

   ____

2. Electric saw

   ____

3. Electric sander

   ____

4. Select an electrical appliance of your choice and describe how it exerts a force over a distance.

   ____

   ____

5. What is the appliance you just described capable of doing?

   ____

6. Make a general statement that describes the relationship between your answer to the last question and electricity.

   ____

   ____

Exploration

Using one piece of wire about 10 cm long, one dry cell, and one bulb, light the bulb. Draw a diagram of the arrangement of the bulb, the wire and the dry cell when the bulb is lighted.

1. How many different points did you touch on the dry cell to make the bulb light?

____

2. How many different points did you touch on the bulb when it lighted?

____

3. Wrap a bulb in a paper towel and strike it gently until the glass globe breaks. Do not strike the glass too hard or you will damage the fine wires you can see inside the bulb. Carefully remove the glass and study how the bulb is made. Draw a picture of how the bulb is made.

4. Describe how the way the bulb is made explains why the bulb had to be touched in the number of places you found necessary.

5. Next connect two dry cells and one bulb. Describe any similarities and differences you see in this hookup and the one with one dry cell and one bulb.

6. Next connect one dry cell and two bulbs together. Describe how this hookup is the same or different from the other two you have made.

The Idea

You know that when wires, dry cells and bulbs are connected in the proper way, the light bulb lights. You also know that a lighted bulb shows that electrical energy is being used.

1. What is the source of the electrical energy?

____

____

2. What is the user of the electrical energy in the hookup you made?

____

An electric energy source and an electrical energy user can be connected in a way that furnishes evidence that electrical energy is being used. That hookup is called an ELECTRICAL CIRCUIT.

Every electrical circuit must have at least one energy source and one energy user. It must also have a way to connect the energy source and the energy user. The connectors, the energy source and the energy user are the circuit elements.

You know that until the circuit elements were connected there was no evidence that energy was being used. The interaction among the elements of an electrical circuit causes an ELECTRIC CURRENT. The electric current moves through the circuit elements.

Name________________________

Section_____________________

Expansion of the Idea

Part 1: Questions on your Observations

You made circuits with one or more bulbs and one or more dry cells.

1. Which circuit had the most current moving through it?

____

____

2. What is your evidence?

____

3. Which circuit had the least current moving through it?

____

4. What is your evidence?

____

Name____________________________

Section_________________________

Expansion of the Idea

Part 2: Using an Ammeter

The **ammeter** is a device that measures how much current is moving through a circuit. Current is measured in amperes. That is why the current measurer is called an ammeter. Study the ammeter and decide how it should be hooked into a circuit. Remember, you want to measure the current moving through the circuit. Describe how the ammeter should be hooked into a circuit.

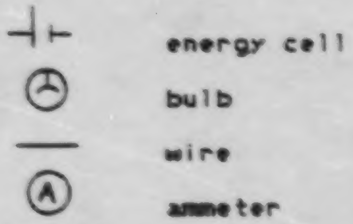
DO NOT HOOK THE AMMETER INTO THE CIRCUIT UNTIL YOUR INSTRUCTOR GIVES YOU PERMISSION

____

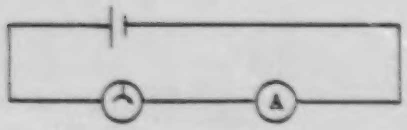
____

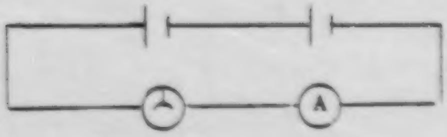
____

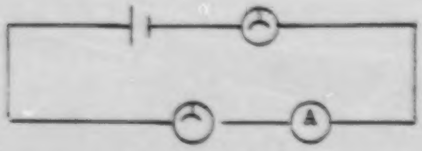
You have drawn pictures of the circuits you made. Using symbols for the circuit elements makes drawing circuits easier. Here are some common symbols used for circuit elements.

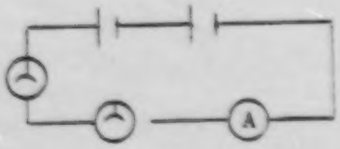


Connect the following circuits and read the value of the current in each one. Electrical current is given the symbol I.









Now read the answers you gave earlier under The Idea about the most current (Questions 1 and 2) and the least current (Questions 3 and 4) in the circuits. You now have evidence from ammeter readings about the currents in the circuits. Combine your earlier answers with the evidence you have from the ammeter readings.

Name________________________

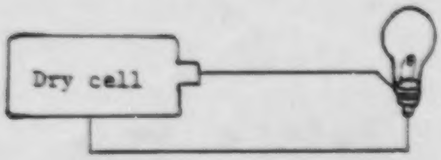
Section________________________

Expansion of the Idea

Part 3: Questions

Investigate each circuit diagram and explain why it will or will not produce a lighted bulb.

Circuit A



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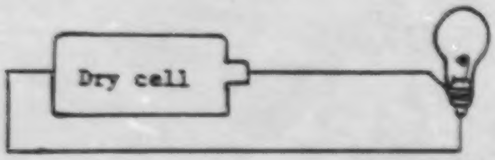
Circuit B



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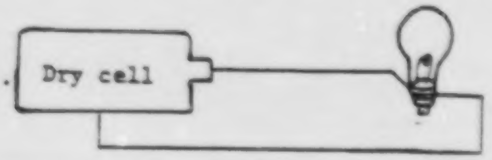
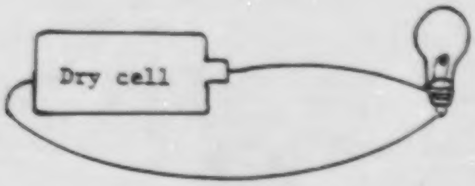
Circuit C



Circuit D



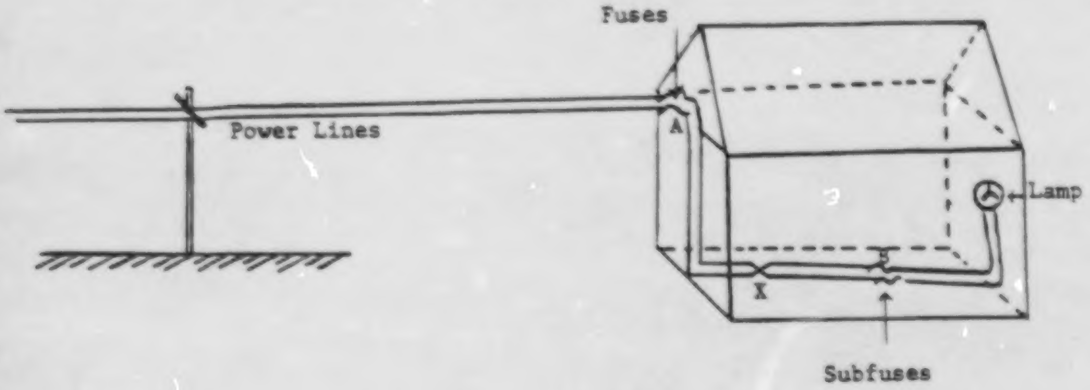
Name______________________

Section____________________

Expandion of the Idea

Part 4: Reading Questions

Suppose wires from some supply running to a lighted lamp and back as in the diagram touch each other by accident, making good metallic contact at X.



1. Which parts of the circuit are likely to be hottest now?

2. The fuses shown are wires of low melting point metal. Which one(s) will melt, if any, A or B?

3. Why is short circuit a good name to describe the phenomenon that results when two wires usually insulated from one another come into contact?

INVESTIGATION 20: CIRCUITS AND CURRENTS

READING: CIRCUITS*

Early electrical knowledge, dating back many centuries, was concerned with electric charges obtained by rubbing things. Electric circuits, with currents to run lamps and motors, did not develop until batteries were invented about 1800. Then the growth was so rapid that it produced not just a part of physics but a new electrical civilization in less than a century.

In this course, instead of following the history, we shall study electricity with modern apparatus in the laboratory; and we shall draw upon your general knowledge of circuits gained from living in a world of cars and electric lighting.

Here are some experimental facts about electric circuits used for house lighting, car lights, electric bells, etc. Some kind of supply--battery or generator or power lines from a power station--is necessary, or nothing happens. To make a lamp light or motor run, a metal wire must go all the way from the supply to the lamp and on from the lamp back to the supply. Inside the lamp there is a thin metal filament; so there is metal wire of some kind all the way from the supply out through the lamp and back again. If this wire is cut, the lamp goes out. A switch is simply a device for making such a cut. A fuse does the same when its wire melts. This continuous metal route is called an electric circuit. If we leave out the lamp and make the circuit of a long piece of thin wire, the whole wire gets warm--something is happening all the way along to warm it. (We have spread the lamp filament's heating all around the circuit.) If some of the wire is thin and some thick, the thin wire gets warm, the thick wire less noticeably so; the filament in the lamp in the first circuit is an extreme case of this. If we shorten the whole length of wire, it gets hotter; still shorter, still hotter. A circuit made of a very short piece of wire all alone might get hot enough to melt or set fire to other things. This is literally a short circuit, and the phrase short circuit is used for any electric circuit which is made so short--or of such low resistance--that there is danger of damage.

INVESTIGATION 20: CIRCUITS AND CURRENTS

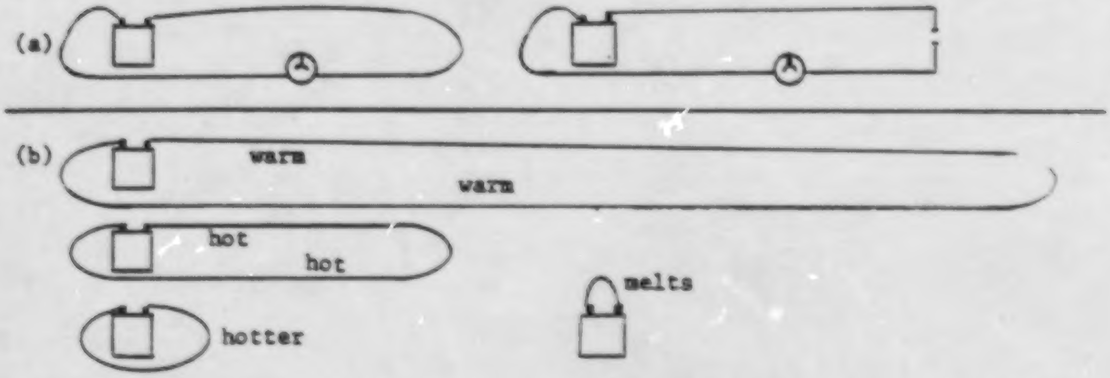


Figure 1. Circuits

To avoid some of the dangers of short circuits, wires are insulated, protected by coatings of non-metal such as rubber, waxed paper, cloth.

Returning to the lamp circuit, we find that if the lamp is moved to some other position in the circuit, it still glows. If several lamps are placed in the circuit in series, they will then all glow equally, but much less brightly than one lamp alone.

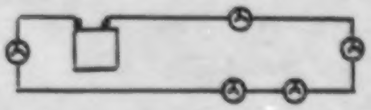


Figure 2. All Lamps Light Equally

Something seems to be available or happening all along the circuit, a ready-to-make-lamp glow state of affairs. Separate experiments with lamp filaments show that this glowing is just a matter of supplying heat to the filament; if we could make it just as hot with a Bunsen flame, it would glow as brightly. So the peculiar electrical property seems to be a supply-heat state of affairs, all around the circuit.

* Taken from Eric M. Rogers, Physics for the Inquiring Mind, Princeton University Press, Princeton, N.J., 1960, pp. 503-504, with permission.

Name ______________________

Section ______________________

Introduction

In Investigation 20, you worked with circuit elements and found out what a circuit is. Write a definition of a circuit.

____

____

____

Discuss your circuit definition with your classmates and teacher and be sure your understanding of the definition agrees with the class. Keep your circuit definition in mind as you complete this investigation.

The energy of a dry cell is proportional to its voltage and is measured with a voltmeter. Your teacher will demonstrate how to use a voltmeter. There is, however, one rule in using an ammeter and a voltmeter you must remember. DO NOT MAKE A COMPLETE CIRCUIT WITH A METER UNTIL THE TEACHER HAS APPROVED THAT CIRCUIT. The instructions given here for you to follow will probably be given to you by the teacher. The instructions here can be used if you need to review the procedure for using a voltmeter.

When you measure a dry cell's voltage, one wire is connected from the positive (+) pole of the dry cell to the positive (+) terminal of the voltmeter. The second wire connects the negative (-) terminals of the dry cell and the voltmeter. The voltmeter then is hooked across the dry cell. Whenever a voltmeter is used to measure (in volts) the energy of any electrical energy source, the voltmeter is always hooked across that energy source. Hooking a voltmeter across means connecting the + terminals together and connecting the - terminals together.

You now will practice hooking a voltmeter across an electrical energy source. The symbol for a voltmeter is V. The diagram shows you how to attach a voltmeter across an energy source.

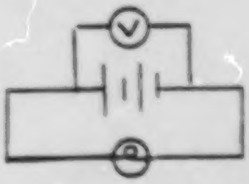


Figure 1

You will be given a voltmeter, wires and three dry cells with which to practice. Record the following data (be sure to number all three of your cells).

Table I

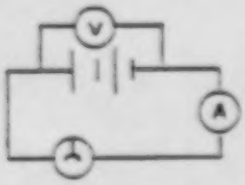
Cell #	Volts	Cells #	Volts
1		1+2	
2		1+3	
3		2+3	

__Exploration__

Connect Circuits One, Two, and Three. Measure and record the voltage (V) and current (I) for each.

Circuit #1:

One bulb

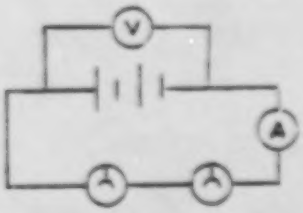


V= _____ volts

I= _____ amperes

Circuit #2:

Two bulbs

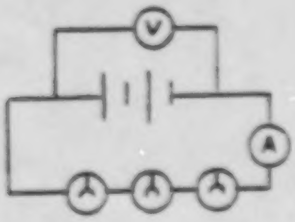


V= _____ volts

I= _____ amperes

Circuit #3:

Three bulbs



V= _____ volts

I= _____ amperes

1. What happens to the current as the number of bulbs increases?

____

____

2. Give an explanation for the effect of the light bulbs that you stated in Question 1.

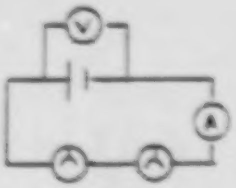
____

____

Connect Circuits Four, Five, Six, and Seven. Measure and record the voltage and the current for each circuit.

Circuit #4:

One bulb

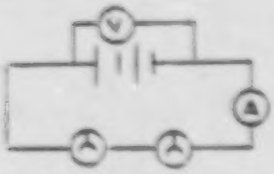


V= ______ volts

I= ______ amperes

Circuit #5:

Two bulbs

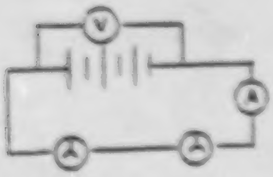


V= ______ volts

I= ______ amperes

Circuit #6:

Three bulbs

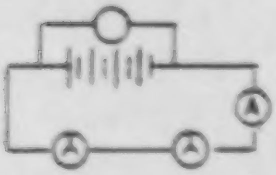


V= ______ volts

I= ______ amperes

Circuit #7:

Three bulbs



V= ______ volts

I= ______ amperes

Using the data from Circuits four through Seven, draw a graph of voltage (V) versus current (I) on the axis below.

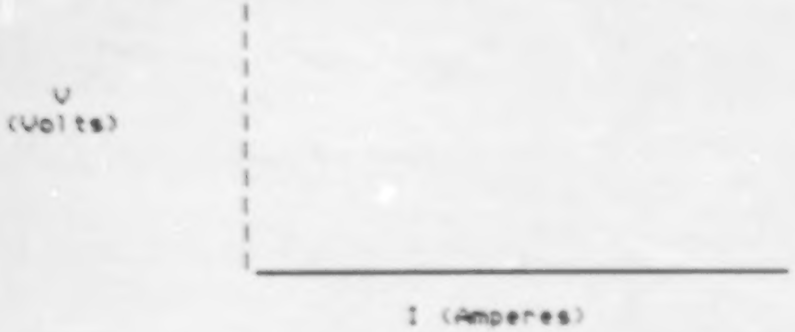


Figure 2

Write a summary of the data collected to this point.

The Idea

1. Using the symbol for Current, I, and R for the number of bulbs in Circuits 1, 2, and 3, write an equation which explains how those two factors (I and R) are related.

2. Using the data from the graph you made, write an equation which explains how V and I are related.

3. You have an equation that relates I and R and one that relates I and V. How are all three variables related?

4. You will be given a name for the relationship you just wrote. Record that name here.

Name ____________________

Section ____________________

Expansion of the Idea

Part 1: Working with Resistors

So far in your work with electrical circuits, you have used light bulbs as resistors in the circuits. When physicists and engineers study circuits, they use special high resistance materials called--reasonably--resistors. These resistors have color-coded rings on their outer coverings. These rings tell the investigator how much resistance the resistor will theoretically give to the circuit. The resistor color-coding scheme is shown below. Your teacher will discuss that scheme with you.

Band 1	Band 2	Band 3
Black-0	Black-0	Black-
Brown-1	Brown-1	Brown-0
Red-2	Red-2	Red-00
Orange-3	Orange-3	Orange-000
Yellow-4	Yellow-4	Yellow-0000
Green-5	Green-5	Green-00000
Blue-6	Blue-6	Blue-000000
Violet-7	Violet-7	Gold-multiply by .1
Gray-8	Gray-8	Silver-multiply by .01
White-9	White-9	

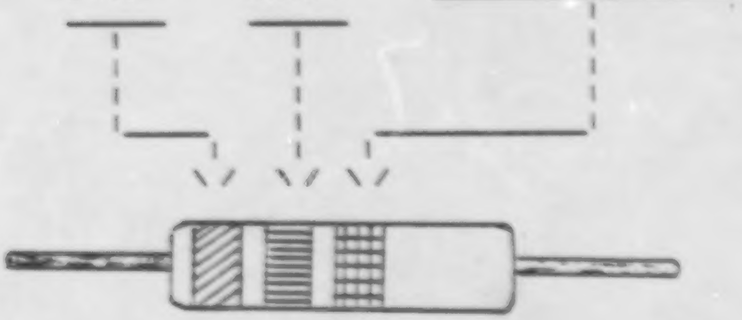


Figure 3

Since the value of a resistor determined from the colored rings represents the theoretical resistance values of the resistors, you should measure the actual resistance of three resistors. Set up circuits to determine the resistance of your resistors. Record the V, I, and R values in Table IV.

Table IV

Resistor	Voltage (volts)	Current (amps)	Actual Resistance (ohms)	Theoretical Resistance (ohms)	Percent Error

Name ______________________

Section ____________________

Expansion of the Idea

Part 2: Applying Ohm's Law to a Specific Circuit Type

Set up the circuit in Figure 4. Four different positions are shown for the voltmeter and ammeter. These positions indicate four different readings for each meter. The total voltage reading, V_T, should be taken when the switch is closed. Take all readings and record them in Table V. Readings from A_T and V_T go on the line labeled Total in the table. Record in Table V the actual resistance values for R_1, R_2, and R_3 from Table IV. Leave the total resistance cell blank.

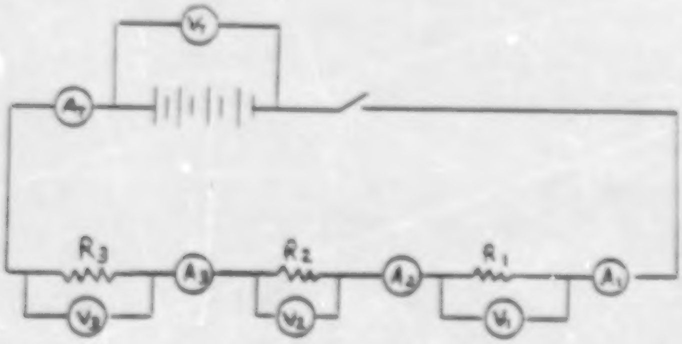


Figure 4

Table V

Resistor	Voltage (volts)	Current (amps)	Resistance (ohms)
R_1			
R_2			
R_3			
Total			

1. How do the four current readings compare with each other?

____

2. What does this tell you about the current flowing through each part of the circuit?

____

3. How are the individual voltages across the resistors related to the total voltage?

____

4. How is the energy distributed in the circuit? Use voltage values to answer this question.

____

____

5. Using the total voltage and the total current, calculate the total resistance of the circuit: $R_T = V_T / I_T$. Record that value in Table V.

____

6. How would you compute the total resistance of a circuit like the one you just worked with for any number of resistors if you knew the values of the individual resistors?

____

____

7. In the circuits you just studied, the voltage, current, and resistance have three distinct characteristics. List them.

   a. The current:

   ____

   b. The resistance:

   ____

   c. The voltage:

   ____

8. When the voltage, current, and resistance have the properties you just described for a circuit, that circuit is called a ______________________________.

Name ____________________

Section ____________________

Expansion of the Idea

Part 3: Circuit Problems

1. What would be the required voltage of an energy source in a circuit with a current of 10 amps and a resistance of 11 ohms?

2. Three 1.5 volt dry cells are connected to compose a battery. The total resistance in the circuit is 100 ohms. How much current moves through the circuit?

3. Using the circuit shown below, using Ohm's Law and your knowledge of series circuits, complete Table VI. (Show your computations.)

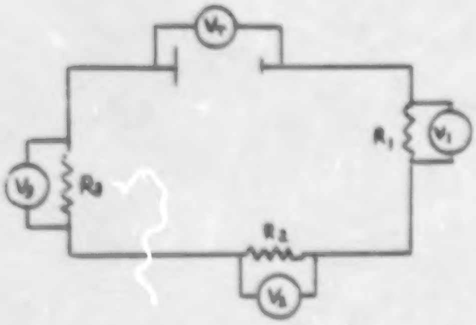


Figure 5

Table VI

	V	I	R
1	6V	.01a	
2	4V		
3			
Total	15V		

Name ____________________

Section ____________________

Expansion of the Idea

Part 4: Applying Ohm's Law to another Specific Circuit Type

Set up the circuit shown in Figure 6. The three positions for each meter indicate three different readings for current and voltage. (You will not hook three voltmeters and three ammeters into the circuit at the same time).

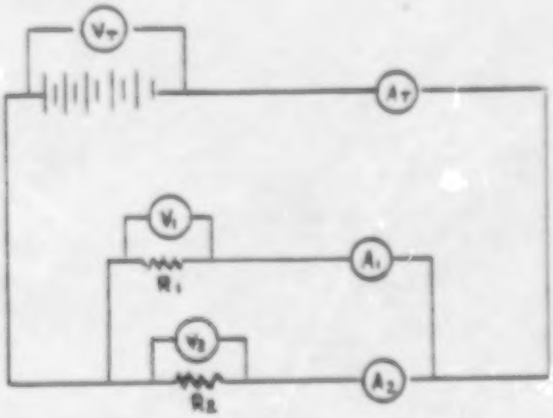


Figure 6

Take all current and voltage readings and record them under I. in Table VII.

Table VII

	Resistor	Voltage (volts)	Current (amps)	Resistance (ohms)
I.	R_1			
	R_2			
	Total			
II.	R_1			
	R_2			
	R_3			
	Total			

Add one resistor to your circuit. See Figure 7. Take the current and voltage measurements on this circuit and record them under II. in Table VII.

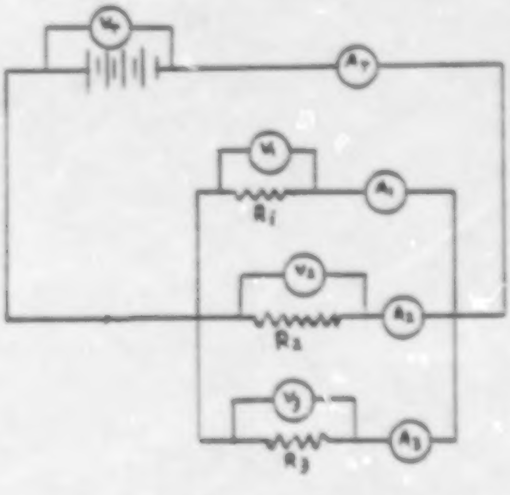


Figure 7

1. How does the voltage drop across each resistor in the circuits in Figures 6 and 7 compare with the voltage of the battery? How is this different from what you found for the series circuit?

2. You learned that current is constant in a series circuit; therefore, the same current exists in each series resistor. What is the relationship between the currents you measured in the circuits in Figures 6 and 7?

3. Explain the flow of current in the circuits in Figures 6 and 7.

4. Calculate $R_1=V_1/I_1$, R_2, and R_3 for the circuits in Figures 6 and 7. Record these values in Table VII.

5. Using Ohm's Law, you can calculate the total resistance of the circuits in Figures 6 and 7. The form of the Ohm's Law equation to use is $R_T=V_T/I_T$. Record those values in Table VIII.

Table VIII

Trial	Equivalent Resistance
I. Two resistors	
II. Three resistors	

6. Compare the two total resistance values shown in Table VIII. How do those total resistances differ from the total resistance of a series circuit?

7. How do the total resistances from I and II in Table VIII compare with the individual resistances of R_1, R_2, and R_3 in the circuits in Figures 6 and 7?

8. Explain how you would compute the total resistance of a circuit like the ones you just worked with for any number of resistors, if you knew the values of the individual resistors.

9. In the circuit you just studied, the voltage, current, and resistance have three distinct characteristics. List them.

   a. The current:

   b. The resistance:

   c. The voltage:

10. When the voltage, current, and resistance have the properties you just described for a circuit, that circuit is called a ______________________________ .

Name ____________________

Section ________________

Expansion of the Idea

Part 5: Circuit Problems

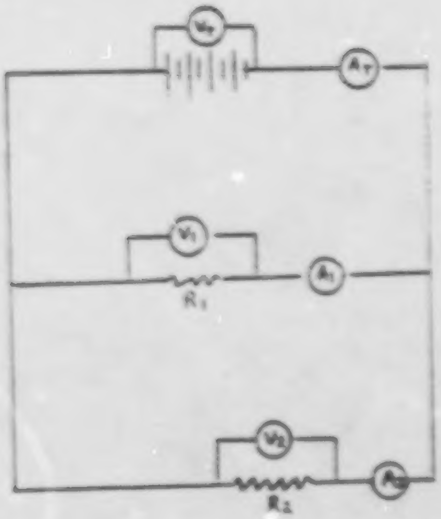
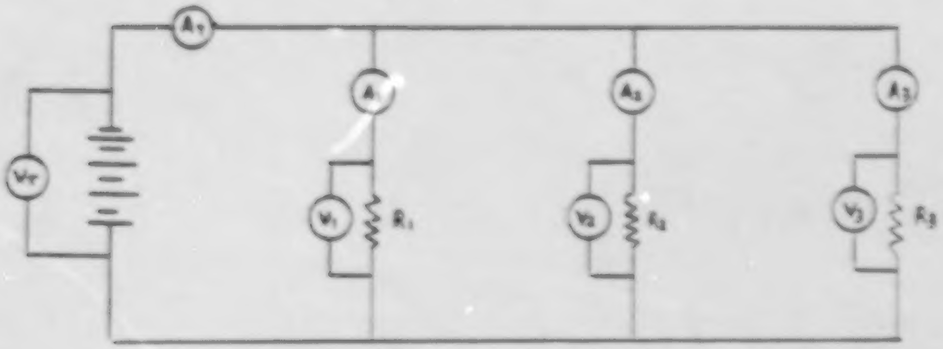


Figure 8

1. Use the figure above to complete Table IX. Show your computations.

Table IX

V (volts)	I (amps)	R (ohms)
V_1= _____	I_1=.1	R_1= _____
V_2=6V	I_2= _____	R_2=12 Ω
V_T= _____	I_T= _____	R_T= _____



A_T
A_1
A_2
A_3
V_T
V_1
R_1
V_2
R_2
V_3
R_3

Figure 9

2. Use the drawing above and complete the blanks below. Show your computations.

V_1=______ I_1=______R_1=250 ohms

V_2-______ I_2=______R_2=500 ohm

V_3=______ I_3=______R_3=750 ohms

V_T=______ I_T=3.0a R_T=______

INVESTIGATION 21: ELECTRICAL CHARGES STUDENT GUIDE

Name ______________________

Section ____________________

Expansion of the Idea

Part 6: Applying Ohm's Law to Complex Circuits

Study the circuit in Figure 10.

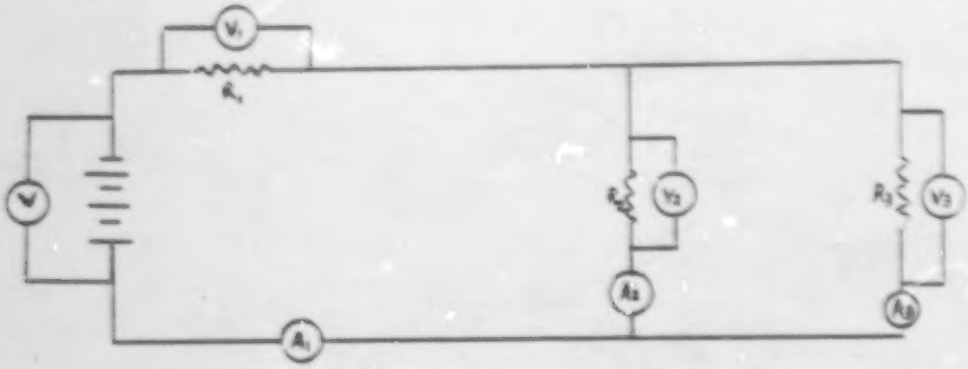


Figure 10

Secure three dry cells from your teacher. Hook them together as shown in the diagram. Use a voltmeter and measure their voltage. Make a record of the value. Next, secure three resistors of known value. Be sure you know the code so you can tell which resistor has which value. Record the values from Figure 10. You now know V_T, R_1, R_2, and R_3.

1. What would be the value of one resistor that could be used to replace R_1 and R_3? Show your computations

2. What would be the value of one resistor that could be used to replace R_1, R_2 and R_3 in Figure 10. Show your computations.

3. In Figure 10, what would be the value of each of the following? Be sure to show your work in each computation.

I_3= V_3=

I_2= V_2=

I_1= V_1=

After you have made predictions for the currents and voltages in the circuit shown in Figure 10, hook up the circuit and measure those values. Explain any serious deviations between the predicted and measured value for the current and voltages.

4. What would be a suitable name for the circuit shown in Figure 10. Explain why you selected the name you did.

Name ____________________

Section ____________________

Expansion of the Idea

Part 7: A Problem

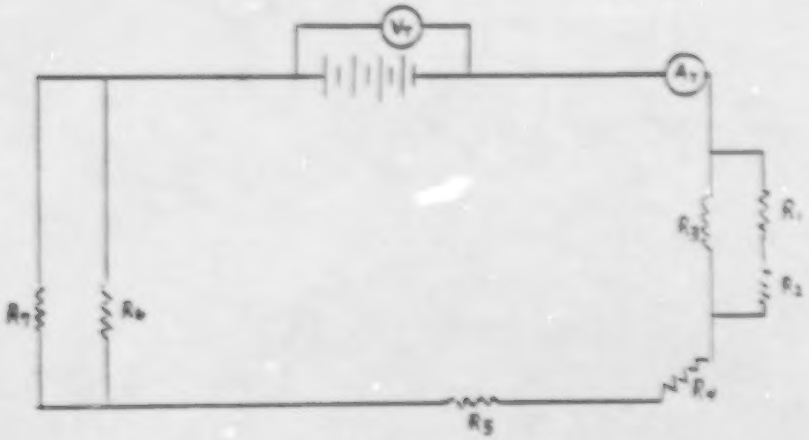


Figure 11

1. Complete the Table below the circuit diagram. Show your computations.

Table X

V (volts)	I (amps)	R (ohms)
V_1=	I_1=.0475a	R_1=50 Ω
V_2=.475V	I_2=	R_2=
V_3=	I_3=	R_3=
V_4=	I_4=	R_4=200 Ω
V_5=	I_5=	R_5=
V_6=	I_6=	R_6=75 Ω
V_7=4.73V	I_7=	R_7=
V_T=	I_T=.076a	R_T=395 Ω

Name ______________________

Section ______________________

Expansion of the Idea

Part B. Reading Questions: Ampere, Ohm, and Volta

1. In the biographical sketch of Ampere, the word electrodynamics is used. Find a definition for this term and then explain in your own words what the term actually means.

____

____

2. In Volta's biography electrometers are mentioned. Before looking up the word, take it apart and decide what it means. Explain the experience you have had with electrometers.

____

____

3. The phrase electromotive force is found in the biography of Ohm. Take the phrase apart and decide what it says to you.

____

____

4. In Investigation 20 your teacher probably discussed the nature of the filament of the light bulb you examined. That filament was composed of the element tungsten which has a resistivity of 5.6×10^{-8} Ω-m at 20°C. The filament itself was a thin wire bent into several loops in order that a great length of wire could be confined in a small space. Hypothesize the effect of using a short, fat wire composed of a metal with a low resistivity like silver (1.6×10^{-8} Ω-m at 20°C).

5. Examine the data in Table I of this reading. Look back at the reading, Conduction and Convection--A Heated Exchange, from Investigation 18. What relationship, if any, exists between the ability of a substance to conduct heat and the ability to conduct electricity?

Name ______________________

Section ____________________

Expansion of the Idea

Part 9, Reading Questions: Using Circuits

1. In the reading, Using Circuits, you were given information concerning how electricity is distributed to, into, and in a house. Now is the time for you to see how your house is wired for electricity. Make a simple sketch of your house. Identify the electrical outlets and switches in each room. (You might want to use symbols like ⊡ for a switch and ⊟ for an outlet.) Find the fuse box or breaker box in your house and determine which fuses or breaker switches affect the various switches and outlets in your house. Draw on your house sketch how you think your house is wired based on the data you collect at the fuse or breaker box. (Colored pencils are useful.)

2. Look at the numbers on the fuses or switches in the fuse or breaker box. Which appliances are in circuits governed by fuses/switches with high amperage ratings?

INVESTIGATION 21: SOME PROPERTIES OF ELECTRICAL CIRCUITS

READING: AMPERE, OHM, AND VOLTA

During this investigation, you have used units for measuring electrical properties which we called the ampere, the ohm, and the volt. Those units of measurement were named for three famous men in the history of electricity. Their names were Andre' Marie Ampere, Georg Simon Ohm, and Count Alessandro Volta.

Ampere, Andre' Marie (1775-1836), was a French physicist and applied mathematician, who helped to establish the science of electrodynamics. He made experiments and formulated laws on the electromagnetic forces between conductors carrying electric currents.

Ampere was born in Lyon on Jan. 20, 1775. Most of his education was private study under the guidance of his father, a wealthy silk merchant. At 14, Ampere had unusual competence in mathematics and a broad knowledge of science. In 1793, during the Reign of Terror, Ampere's father was executed.

After a happy marriage in 1799 and the birth of a son in 1800, he became a professor of physics in Bourg (1801-1803). A mathematical paper on game theory then gained him a post at the lycee in Lyon. On his wife's death he left in 1804 for Ecole Polytechnique in Paris, and he taught in Paris for the rest of his life. He was elected to the Academy of Science in 1814.

At a meeting on Sept. 11, 1820, the Academy was told about H.C. Oersted's discovery that a compass needle deflects when it is near a wire carring an electric current. At subsequent meetings in September and October, Ampere showed that two nearby conductors carrying electric currents exert forces on each other, and he developed the mathematical laws for calculating such forces. He demonstrated that a long helical coil carrying current was magnetically similar to a bar magnet, and he showed that a piece of iron inserted in such a coil became strongly magnetized. He interpreted the magnetic forces between permanent magnets as forces between molecular electric currents in the iron. Initial criticism that part of his theory contradicted Newton's law of equality of action and reaction soon subsided, and Ampere's laws of electrodynamics gained universal acceptance and admiration. These laws became a basic element of J. C. Maxwell's electromagnetic theory in 1865.

INVESTIGATION 21: SOME PROPERTIES OF ELECTRICAL CIRCUITS

Ampere, who was an ingenious experimenter, proposed a current-measuring galvanometer and a 26-wire electromagnetic telegraph, both based on Oersted's observation. He also suggested the rotating switch (communtator) first used on H. Pixii's electric generator in 1832. Ampere made other contributions in the fields of mechanics, optics, statistics, chemistry, and crystallography. He died in Marseille on June 10, 1836.

The ampere, the unit of electric current, is named after him. A law, now called Ampere's law, gives a quantitative expression for the force between two arbitrarily oriented current elements in a uniform medium.[1]

Ohm, Georg Simon (1789-1854), German physicist who discovered the principles concerning the flow of current through a conductor that are expressed in Ohm's Law. He was born in Erlangen, now West Germany, on March 16, 1789, the son of a master mechanic. After attending the University of Erlangen, he taught physics and mathematics at the Realschule in Bamberg (1813-1817) and at the Jesuits' College in Cologne (1817-1826).

The repudiation of his new theories forced him to spend the following six years ignominiously as a private tutor in Berlin. In 1833 he was made director of the Polytechnic School of Nuremberg, and in 1849 he was awarded a professorship in physics at the University of Munich. He died in Munich on July 7, 1854.

During the productive years of his life he was always in reduced financial circumstances, and as a result his experimental equipment was crude and his discoveries originally appeared in a series of minor publications. The primary importance of his work lies in his careful investigation of galvanic currents, his discovery of the distribution of electromotive force in an electrical circuit, and his accomplishment in establishing a definite relationship connecting resistance, electromotive force, and current strength. He also experimented with optics, acoustics, and the electrical conductivity of liquids.[2]

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[1] Taken from the Encyclopedia Americana, International Edition, New York, Vol. 1, 1984, p. 754.

[2] Taken from the Encyclopedia Americana, International Edition, New York, Vol. 21, 1984, p. 673.

INVESTIGATION 21: SOME PROPERTIES OF ELECTRICAL CIRCUITS

Volta, Count Allessandro, Italian physicist, chemist, and discover of constant-current electricity: b. Como, Italy, Feb. 18, 1745; d. there, March 5, 1827. His first electrical publications, in which he described improved electrometers, appeared in 1769 and 1771. He became professor of physics at Como in 1774 and five years later professor of natural philosophy at Pavia, where he remained for 25 years. Volta made improvements in the electrophorus (q.v.) in 1777 and in the electroscope (q.v.). After analyzing marsh gas he published his most popular treatise, Lettere sull aira infiammabile delle paludi (1776); and another paper on an improved electroscope appeared in 1782. A series of inventions followed, including an eudiometer, an electric piston, and a lamp that burned inflammable air.

Prompted by Luigi Galvani's treatise on animal electricity (1791), Volta commenced a new series of experiments that resulted in his announcement on March 20, 1800, of his discovery of the voltaic pile, the first source of constant-current electricity. He communicated the results of his work to the Royal Society of London, which published the experiments in its Philosophical Transactions in 1800. With this he and other scientists decomposed water by electrolysis, electroplated precious metals, formed the electromagnet, and thereby opened the electrical age.

At the invitation of Napoleon I, Volta went to Paris in 1801 and performed experiments before the Institut de France. To honor the occasion a gold medal was struck, a sum of 6,000 francs was awarded to him, and a commission was created to repeat his experiments. He also was granted the title of count and made a senator of the kingdom of Lombardy; later he received the Cross of the Legion of Honor.[3]

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[3] Taken from the Encyclopedia Americana, International Edition, New York, Vol. 28, 1984, p. 227.

INVESTIGATION 21: SOME PROPERTIES OF ELECTRICAL CIRCUITS

READING: USING CIRCUITS

The electricity used in homes, businesses, and all through society is available because of electrical circuits. You know the basic properties of series and parallel circuits. You can, therefore, understand how electricity is delivered to homes, stores, schools andother places in a community.

To understand the practical use of electrical circuits you must first understand the idea of voltage rating. A light bulb or any other electrical appliance has stamped on it 110-115 V. That means that the appliance has been made to operate when that voltage (110 V) is put across it. You found that in a parallel circuit, each branch had the entire voltage of the battery of cells across it.

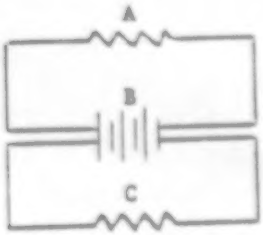

Figure 1

In Figure 1, Resistor A touches the positive and negative terminals of the Battery B. Resistor C also touches both sides of Batter B. Each resistor has the complete voltage of the battery across it. The resistors are hooked in parallel with each other and the battery. Resistor A represents a branch of the total circuit and Resistor C is a second branch. Each branch has the total voltage of the battery placed across it.

The voltage rating of an appliance tells users at what voltage the appliance was manufactured to operate. If more voltage is placed across it, more energy is being given to the appliance than it can use. The probability is that the appliance will be burned up. If less than the rated voltage is applied across the appliance, the appliance will not operate at all or will not operate as it should. A light bulb, for example, which has a voltage rating of 110 V will be dim if 85 V are applied across it. An Electric mixer that was rated at 110 V and had 85 V applied across it will run slower at its top speed than at 110 V. Some appliances will not work at any voltage other than their rated voltage. Som radios will not operate below 100 V.

INVESTIGATION 21: SOME PROPERTIES OF ELECTRICAL CIRCUITS

Any circuit (that is to operate appliances) in a house must deliver the rated voltage of the appliances. If you think of the voltage source for an appliance as a battery of cells, each appliance must have its battery and all those batteries must have the same voltage. A battery for each appliance in a house would be inconvenient, expensive, and probably dangerous. How is a battery of like voltage provided in a house for each appliance? The answer to that question is power stations, substations, transformers and outlets are used.

The voltage used in houses is generated at the power station. Now the voltage generated there is probably much greater than 110 volts, but that is not important at this point. Just think of the power station as a 110 volt source. The electrical power goes from the power station directly to neighborhood transformers or power substations. In large communities, power substations are used and the power goes from them to transformers. Each transformer serves several homes or businesses. Think of the power station as being a 110 volt source for the substation. The substation is a 110 volt source for the transformer which is a 110 volt source for homes. (The voltage delivered to the homes is 110 volts but that is probably not true at power stations, substations, or transformers. Do not let that concern you.) The picture explains how this can happen. The parallel circuit is the answer.

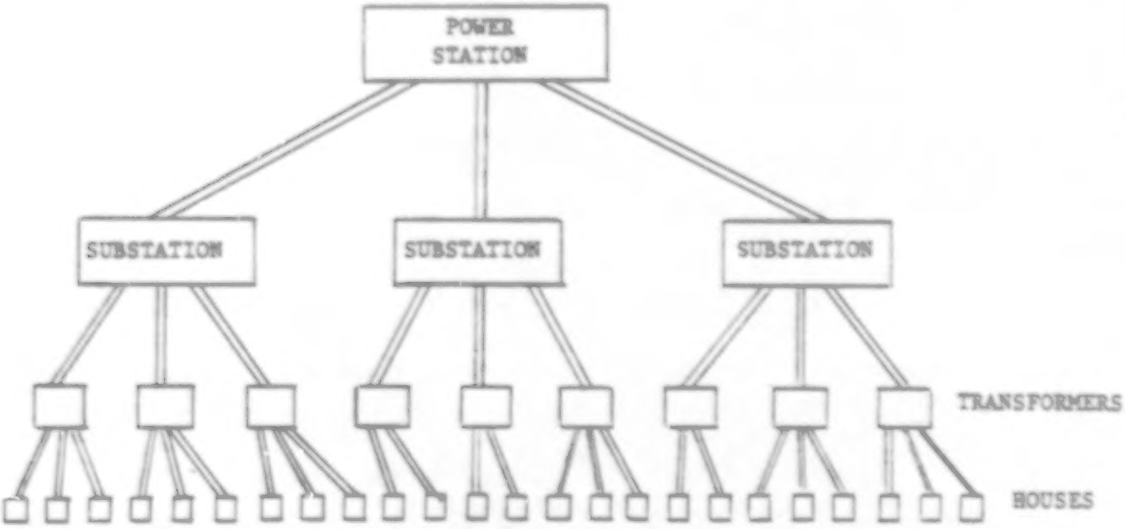

Figure 2

INVESTIGATION 21: SOME PROPERTIES OF ELECTRICAL CIRCUITS

Each substation is hooked directly across the power station. Each transformer is hooked directly across each substation and each house is connected directly across each transformer.

If you locate the transformer servicing your house, you will see that two wires run from the transformer to the house. If you measured the voltage between those wires it would read 110 V. The wires are hooked to the meter on your house. So the meter on your house is its 110 V battery. That battery must serve every appliance in the house. How can that be done? The answer is again the parallel circuit.

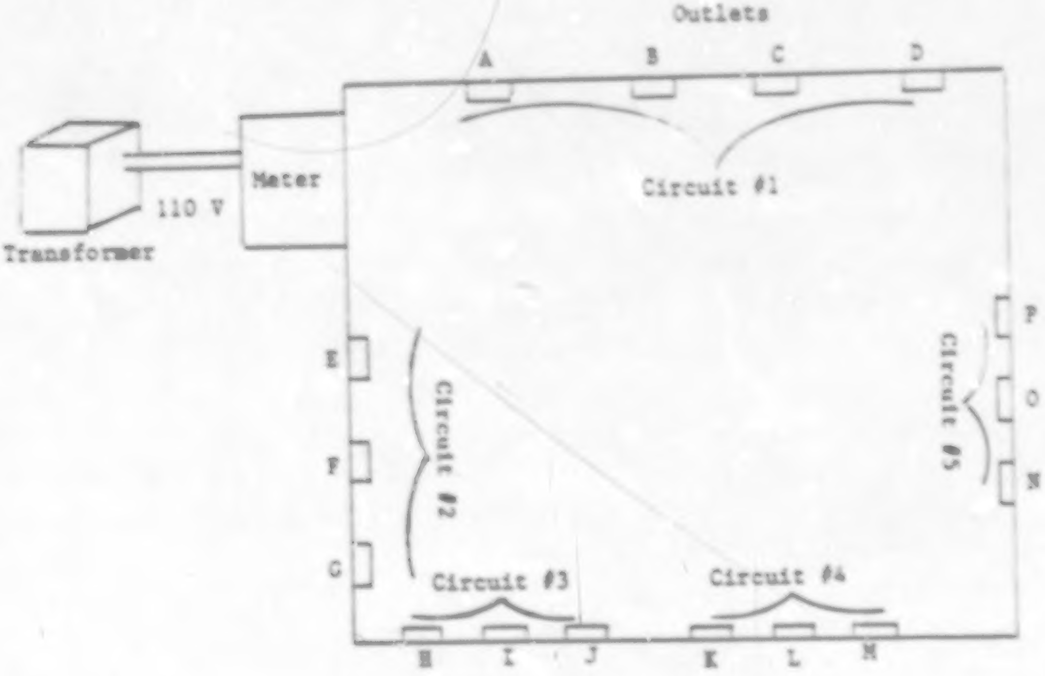

Figure 3

Figure 3 shows a house that has 16 electrical outlets. Now an electrical outlet gets its name from a place where electrical energy at 110 volts is available. That outlet might be a light switch that controls built-in lights. It also might be a place where appliances can be plugged in. Two wires must connect each outlet directly across the meter--the 110 V battery for the house.

INVESTIGATION 21: SOME PROPERTIES OF ELECTRICAL CIRCUITS

There are several ways to deliver 110 volts to each outlet. But first lets find out how an outlet works. When wires are connected as shown in Figure 4, it means that wire CD does not touch wire AB. Figure 5, therefore, shows that each outlet is hooked directly across the meter. Each outlet is a 110 V battery--or source--for appliances.

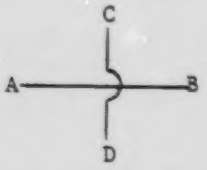

Figure 4

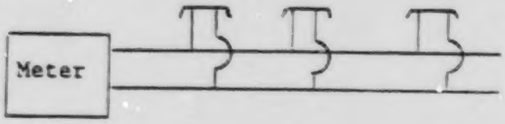

Figure 5

From your investigations of parallel circuits you know that as more resistors (appliances) are connectd in parallel, the total resistance of the circuit drops. As the resistance drops, the current in the circuit increases. The more appliances you turn on, therefore, the more current flows. Electrical current, as you found in your investigation, causes wires to get hot. As the current flowing increases, the wires get hotter and hotter. Eventually, a fire would start and the building would burn.

There are two ways to prevent fires caused by too much current in a parallel circuit. The first procedure used is called a fuse. Study Figure 6.

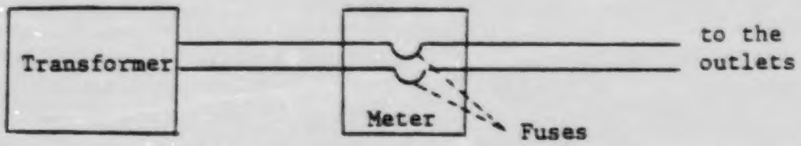

Figure 6

INVESTIGATION 21: SOME PROPERTIES OF ELECTRICAL CIRCUITS

The transformer is hooked directly to the meter. At the meter they meet two (or one) metal strips that have a very low melting point. When the current gets too high, the fuses melt and open the circuit. The current stops flowing and the danger of fire is eliminated. Fuses are rated by the number of amperes that can flow through them without them melting. If a fuse has 20 a stamped on it, that information tells you that any current over 20 amperes will melt that fuse.

In some homes, there are no fuses at the meter or in a metal box on the wall called a fuse box. Instead the fuse box contains a series of switches. Those switches are called circuit breakers. If you look at the circuit breakers carefully, you will find that each one has a number stamped on it. That number tells you the amount of current, in amperes, that can flow through the circuit breaker before the switches spring open. A circuit breaker usually contains two switches. (When a circuit breaker opens, it is said to trip.) A circuit breaker is closed by pushing the two swithes to the off position and then back to the on position. Before resetting the circuit breaker some of the appliances must be removed from the circuit (unplugged or turned off) otherwise when you reset the circuit breaker the circuit will still carry too much current. The circuit breaker will again trip and the circuit will again be open.

Circuit breakers and fuses are equally effective. But circuit breakers are safer for people who try to fool the rules of a parallel circuit. Sometimes a fuse burns out and another one is not available. Now remember the fuse burned out because the amount of current moving in the wires of the parallel circuit will cause a fire. Some persons, who do not understand parallel circuits, put a copper penny in the socket behind the fuse. The fuse has just been bypassed; that is, the current flows through the penny instead of the fuse. The penny will not burn up when a dangerous amount of current flows through it, but the house will! For persons who try to fool the rules of a parallel circuit, circuit breakers are best because they cannot be fooled. Circuit breakers operate upon an electrical principle you have not studied yet.

The second procedure to use in preventing fuses from carrying too much electrical current is the multiple circuit principle. Look at Figure 3. Imagine that two wires ran from the meter to all the outlets in Circuit #1. Each of the outlets would be connectd to the wires as shown in Figure 5. Between the meter and Circuit #1, fuses would be placed. Those fuses would allow only the amount of current to flow in Circuit #1 that the wires could safely carry. Two wires would run from the meter to each of the Circuits shown in Figure 3. That house would be a five parallel circuit house. It would require five sets of fuses and/or circuit breakers. The five circuits would be hooked in parallel with the meter. Each appliance in each circuit is hooked in parallel with each other and the meter. In other words, each appliance is hooked directly across the meter--the giant battery for the entire house and each otlet in it.

There is a great advantage to the multiple parallel-circuit house. Look at Figure 3 again. Suppose someone plugs in appliances in Circuit #1 that draw more current than the fuses can carry. The fuses melt (or the circuit breaker opens). That part of the house has no electricity until the fuses are replaced (or the circuit breaker is reset). But Circuits 2 through 5 still work as usual. When one circuit in a multiple circuit house stops working, the other circuits continue to function. That is, of course, one of the advantages of a parallel circuit; just because one part stops working, the rest of the circuit does not.

The advantage of a parallel circuit is the big disadvantage of a series circuit. When one part of a series circuit stops working, the entire circuit stops because in a series circuit the entire current must flow through each part of the circuit.

The most common series circuit that you have probably experienced is a flashlight . The diagram in Figure 7 shows the circuit of a flashlight.

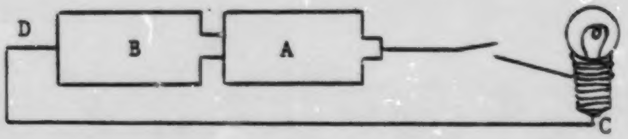

Figure 7

INVESTIGATION 21: SOME PROPERTIES OF ELECTRICAL CIRCUITS

The positive end of one 1 1/2 volt dry cell is touching the negative end of the other 1 1/2 volt dry cell. The total voltage is less than 3 volts. The cell's voltages are added directly because they are in series. The current leaves the top of dry cell A and, when the switch is closed, enters the bulb. The current then returns to the dry cells through wire CD. In practice the metal case, a metal spring at the bottom of the case, and the reflector in the flashlight substitute for wire CD. The diagram of the flashlight shows how the switch works. The reflector is insulated from the case. The switch makes contact with the metal reflector by a sliding piece of metal. The metal piece connects the reflector and case. That then makes a complete circuit. All the current goes through all parts of the circuit so it is a series circuit.

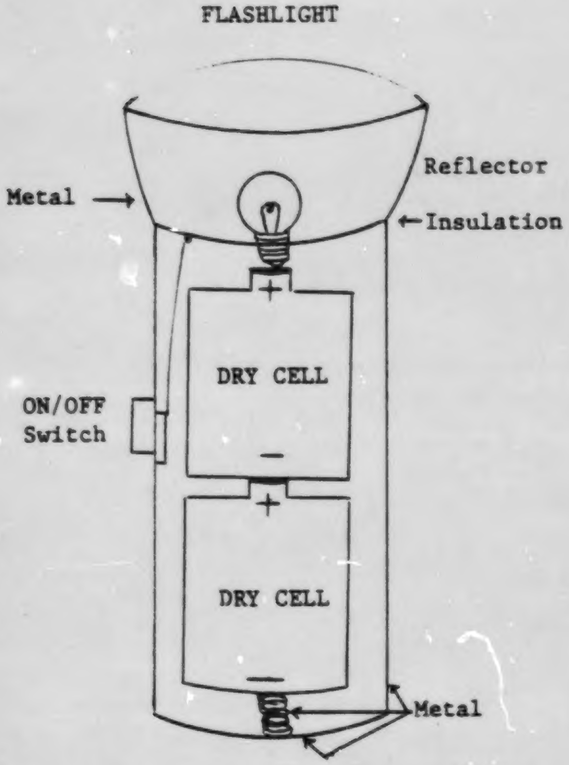

Figure 8

One type of Christmas tree lights has a series circuit. Those lightbulbs are all connected with only one wire. All the current passes through each bulb. If one bulb burns out, an open circuit is produced and no current can flow. Finding the one bulb that is open, however, can be quite a task.

Heating elements for appliances usually consist of coiled wires spread evenly throughout the appliance. Generally those element parts are hooked in series. In a toaster, for example, the element parts being hooked in series is desirable. Suppose, for example, that the different parts of the heating element were hooked in parallel. When one part burned out, the others would keep working. The toast would toast unevenly. A series circuit keeps that from happening.

INVESTIGATION 21: SOME PROPERTIES OF ELECTRICAL CIRCUITS

READING: VIVA LA RESISTANCE

Your first experiences with circuits in this and the previous investigation, involved using light bulbs as resistors. You determined from your data concerning current and voltage that the light bulb resisted the current. In the latter portion of this investigation you experienced a device called a resistor. It probably was composed of a carbon or glass center and acted to resist the current just as the light bulb had done. You found the various resistors affected the current to differing degrees. A 100 ohm resistor had much less effect on the current than a 600 ohm resistor.

Perhaps you have connected and disconnected the circuits and thought little about the factors--both physical and environmental--that might affect the resistance in the circuit. For example: how do different materials affect resistance? How does the wire connecting the parts of the circuit affect resistance? How does temperature affect resistance? Knowing the answers to these questions may be important to you at some point since your data have indicated that current decreases proportionally with an increase in resistance.

Before we go any further, you need to familiarize yourself with the language of resistance. You will recall from your investigations concerning heat that materials that transferred heat well were said to be good conductors. Such is also the case in electrical circuits--a substance that transfers electricity well is said to be a good conductor of electricity. A material that does not transfer electrical current well is a good resistor. You know that resistance is measured in the unit of the OHM. Interestingly enough, the unit of conductance is called the MHO. (Scientists have a sense of humor after all.) If asked to name a good conductor of electricity, you should have a quick answer. What material have you been using to connect the parts of your circuits? More than likely you have been using copper wire surrounded by a rubber cover. Copper is a very good conductor of electricity. (Rubber is not a good conductor and is thus commonly used as an insulator in electrical wires.) Silver is also an excellent conductor, but it is much too expensive to be used in common electrical circuits. Gold, aluminum, and most other metals are acceptable conducting materials. Wood, glass, sulfur, quartz, and air are very poor conductors of electricity.

INVESTIGATION 21: SOME PROPERTIES OF ELECTRICAL CIRCUITS

We have been speaking of the conducting ability of various materials. Phyicists, however, would likely refer to the resistivity of a substance. As you would expect, materials that are good conductors have a very low resistivity, while poor conductors have a high resistivity. Resistivity is a constant (symbolized by the Greek rho, ρ) dependent on the material of which a wire or other object is made. Table I lists the resistivities of several substances.

Table 1

Substance	Resistivity (Ω-meters @20°C)
Silver	1.52×10^{-8}
Copper	1.54×10^{-8}
Gold	2.27×10^{-8}
Aluminum	2.63×10^{-8}
Germanium	2.00
Silicon	3.00×10^{4}
Maplewood	3.00×10^{8}
Glass	1.00×10^{12}
Sulfur	1.00×10^{15}
Quartz	5.00×10^{17}

How do the physical dimensions of a wire affect the resistivity? Would one prefer to use a short, fat wire or a long, thin wire when connecting a light bulb to a dry cell? Think about a garden hose. What kind of hose would deliver the greatest quantity of water? You probably would want to choose a hose with a large diameter and a fairly short length. In like manner a short wire with a large cross-sectional area (or large diameter) has a lower resistance than a long wire with a small cross-sectional area. Thus, resistance (R) is directly proportional to the length (L) of the wire and inversely proportional to the cross-sectional area (A) of the wire. In equation form $R=\rho(L/A)$ where ρ is the resistivity constant.

INVESTIGATION 21: SOME PROPERTIES OF ELECTRICAL CIRCUITS

If we rearrange the equation to solve for ρ, we see that the unit of ρ to be the ohm-meter since $\rho = R(A/L) - \text{ohm}(m2/m) = \text{ohm-meter}$. This may all seem very complicated, but actually the equation tells us that the resistance (R) a certain object lends to a circuit is dependent on the object's length (L), cross-sectional area (A), and the material of which it is made (represented by the constant ρ).

You may have noticed that the resistivity values in Table I are quoted for materials at 20°C. Resistivity is dependent on temperature. Would you expect resistivity to increase or decrease with a decline in temperature? Think back to your work with heat. You will recall that heat is a form of energy and is, thus, capable of doing work. When heat energy is transferred to the molecules of a substance, the motion of the molecules increases lending to an increase in their kinetic energies. This increase in kinetic energy is registered as a rise in the temperature of the substance. How does this relate to the resistivity of a material? As the temperature of the material rises, the molecules within the wire move faster and faster and the current in the circuit is impeded more and more. The effect of temperature can be likened to the movement of a person down a crowded hallway. If the other people in the hall are standing still or moving slowly (likened to molecules in a low temperature situation), you can pass down the corridor with little effort. However, if the people in the hall are running around, bouncing off the walls, and generally acting crazy, you will have much difficulty passing down the hall.

There is an exception to the direct relationship between temperature and resistivity. Substances such as germanium and silicon have moderate resistivities and their resistance decreases as the temperature goes up. These materials are called semiconductors. Semiconductors are very important in many of the highly technical devises prevalent today. If you are interested in computer technology, you might want to find out more about semiconductors.

Name________________________

Section_______________________

Introduction

In the last three investigations you have been working with currents and voltages. You have been told that the voltage of a cell is a measure of its energy. An electric current has been defined as the result of the interaction among the circuit elements. In this investigation you are going to probe behind those definitions of current and voltage. We have said a current flows. What is moving? To what does a dry cell give energy? During this investigation, you will build some mental models that may help you answer those questions.

Examine the device you are given: it is called an electroscope. Notice that inside it has very thin metal leaves hanging freely at the end of the long, metal rod. That metal rod has a metal knob at the end outside of the container. You will also find that the metal rod is held away from the case by a rubber stopper, a piece of plastic, or some other like material. If the case of your electroscope is metal with glass panels, notice that the metal rod is carefully held away from the metal case. The material used will not permit electricity to pass from the rod to the case. Such material is called insulation. An object made of such material is known as an insulator. The diagram shows two electroscopes. One has a metal case and the other's case is an Erlenmeyer flask. The insulator in the Erlenmeyer flask electroscope is a rubber stopper.

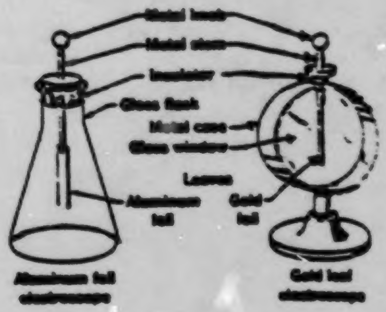

Figure 1

Examine the leaves of the electroscope. They should be hanging straight down. If they are not, gently touch the knob with your finger. That action should make the leaves hang straight down. Remove your finger.

Exploration

1. Use the piece of wool and rub the hard rubber (HR) rod vigorously. Now hold the HR rod very near the electroscope's knob. DO NOT TOUCH THE KNOB. Explain what happens.

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2. Next, use the silk and rub the glass rod vigorously. Hold the rod near the knob of the electroscope. DO NOT TOUCH THE KNOB. Record what you observe.

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3. How is what you observed when the wool-rubbed HR rod was held near the electroscope different from what you saw when using the silk-rubbed glass rod.

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4. Touch the knob of the electroscope with your finger. Be sure the leaves are hanging straight down. Use the piece of silk and again vigorously rub the glass rod. Now touch the newly-rubbed glass rod to the knob of the electroscope. Maintain contact between the knob and the rod until the full length of the rod has been rubbed on the electroscope's knob. Remove the rod and observe the leaves. Record your observations.

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5. Once again, rub the glass rod vigorously with the silk. While you are doing that, one of your laboratory partners should be vigorously rubbing the HR rod. Contact the electroscope's knob with the glass rod just as you did before. WATCH THE METAL LEAVES OF THE ELECTROSCOPE VERY CAREFULLY. Have your laboratory partner touch the electroscope's knob with the newly-rubbed HR rod. Rub it along the knob just as you did the glass rod and then quickly remove it. Observe what happens to the electroscope's leaves. You may have to repeat this procedure several times to observe exactly what happens to the leaves of the electroscope and the order of the events that happened. Record your observations.

6. How can your observations be interpreted?

So far you have worked with hard rubber and glass rods that have been rubbed with wool or silk. Maybe those rods will cause the leaves of the electroscope to behave as they do without rubbing them. That possibility needs to be checked.

7. Touch a finger to the knob of the electroscope. Do that as many times as necessry until the electroscope's leaves are hanging straight down. The leaves should look exactly a they did when you first examined the electroscope. Pull your closed hand all the way along the HR rod. Touch the rubber rod to the knob of the electroscope. Compare what you observe to what you observed when the rubbed rubber rod was touched to the electroscope. Record that comparison.

8. Again touch a finger to the knob of the electroscope. Pull the glass rod through your closed hand. Next touch the glass rod to the knob of the electroscope. Compare what just happened with the observations you made when the rubbed glass rod was touched to the electroscope's knob. Record that comparison.

9. What do the data from Questions 7 and 8 permit you to infer about what happened to the rods when they are rubbed and to the electroscope's leaves when the rubbed rods contact the electroscope's knob?

The Idea

You know that the aluminum foil has mass. A force, therefore, is necessary to move it and you saw it move. The movement occurred when the rubbed rods were brought near or touched the knob of the electroscope. Something about rubbing the rods permitted them to generate a force great enough to move a mass. In other words, the rubbed rods gave the electroscope's leaves energy.

10. Using the idea of work, explain why the above statement is true?

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The energy used in lifting the electroscope's leaves began with the rubbed rods. When the rods were rubbed, they gained an

ELECTRICAL CHARGE.

That electrical charge was responsible for producing a force that caused the leaves to move.

Name______________________

Section____________________

Expansion of the Idea

Part 1: An Interpretation

How can the electrical charge on the rubbed rod be responsible for generating a force that causes the movement of the electroscope's leaves? To answer that question you need to consider the data you collected by touching the rubbed rods to the knob of the electroscope. (Rubbed glass or hard rubber rods are charged rods). Think about these data.

When you touched the silk-rubbed glass rod to the electroscope's knob, the leaves parted and remained apart.

When you then touched the wool-rubbed hard rubber rod to the electroscope's knob, the leaves collapsed to their beginning position. The leaves then parted again and remained apart.

11. What do those data tell you? Record your interpretations here.

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12. Interpretations of experimental data like the ones you just recorded can lead to rules you can use. State the above data interpretation as a rule.

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13. Again, turn your attention to the data interpretation from which you wrote the rule in Question 12. In the space below explain why the rule you just wrote is justified. You will probably need to re-study the data you collected when you touched the electroscope's knob with the charged rods.

There are two kinds of charge and they are opposite to each other. Because of the *oppositeness* these charges have been named positive (+) and negative (-). When an object has equal numbers of positive and negative charges, it is *electrically neutral*. All non-charged objects are electrically neutral.

14. In the first portion of this investigation, you found that just holding a charged rod near the electrically neutral knob of the uncharged electroscope caused the leaves to move. In other words, force enough to do the work of lifting the leaves was generated. You also know the rule about attraction and repulsion of charges. Combine those ideas and explain why just bringing a charged rod near the electroscope's knob causes the leaves to separate.

Name________________________

Section_______________________

Expansion of the Idea

Part 2: An Experiment

You have just finished experimenting with putting an electrical charge on an object by rubbing it. You then charged the electroscope. When electrical charges are placed on an object, those charges are called static (at rest) electrical charges. That area of physics that deals with electrical charges at rest is called static electricity. The most common example of the buildup of static electricity is lightning. A cloud stores electrical charge until it cannot hold any more then the cloud gives (discharges) its charge to another cloud or to the earth. When the charged cloud discharges to the earth, lightning has struck. Now evaluate the probable accuracy of the saying "Lightning never strikes twice in the same place."

In this portion of the investigation you are going to study a new property of electrical charges. You will need the copper object shown in Figure 2.

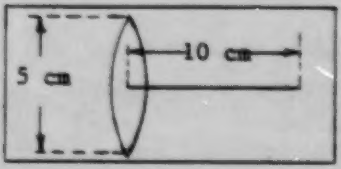

Figure 2

Set the copper object across the top of a beaker, glass jar, or styrofoam cup. Hang a narrow piece of aluminum foil in front of the object's disc so there is contact between it and the foil (see Figure 3).

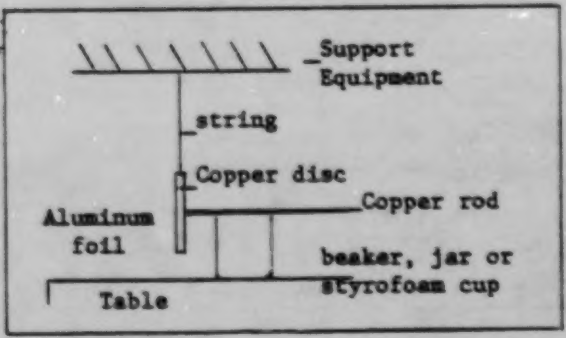

Figure 3

Charge the HR rod and rub it along the metal rod which is attached to the disc. DO NOT TOUCH THE DISC.

15. Observe the behavior of the aluminum foil. Record those observations.

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16. Repeat the experiment by charging the glass rod. Before you use the glass rod, touch your finger to the disc. That removes any charge which might be there. That is the process called grounding. Perform all combinations of rods for charging the disc. Describe what has happened. Record your interpretation here.

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17. Remember that you did not touch the disc with the charged rod. Explain how the electrical charge got from the metal rod to the disc.

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The movement of charges along the metal is called an

ELECTRICAL CURRENT.

18. What would be a suitable name for a material--such as the metal rod--that allows current to move through it?

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An electrical current is a movement of electrical charge.

Name____________________

Section____________________

Expansion of the Idea

Part 3: An Interpretation

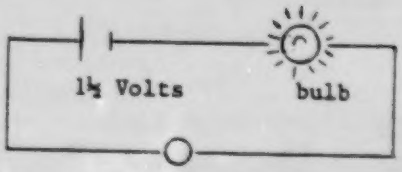


Figure 4

19. Connect the circuit shown in Figure 4. Use the ideas of electrical charge and current and write an explanation of why the bulb lights. Be sure to use the terms electrical charge and electrical current in your explanation.

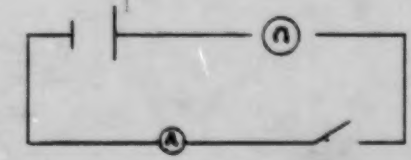


Figure 5

20. Your instructor will now set up the circuit shown in Figure 5 and do a special demonstration for you. When compared with the circuit in Figure 4, what did the special demonstration show?

Name ____________________

Section ____________________

Expansion of the Idea

Part 4: A Summary

Which way does the current actually flow in a circuit? When people began the serious study of electricity, the assumption was made that current flowed out of the positive pole of a cell, through the circuit and returned to the negative pole. Now go to the reading entitled, Edison's Experiment, and read about the experiment done by Thomas A. Edison when he was studying the flow of electrical current.

21. In the introduction to this investigation this question was asked: To what does a dry cell give energy? Go back to the statement made about current and electrical charge and write an answer to that question below.

22. Combine what you just wrote with the results of Edison's experiment. What type of electrical charges does the dry cell give energy to?

23. That type of charge has a special name. Write it here.

To develop a complete understanding of the relationship between energy and electrical current, you need to do some reading. Go to the reading Electrical Potential Difference and complete it.

24. What is electric potential difference? What equation could you use to identify the nature of the volt?

Name____________________

Section____________________

Expansion of the Idea

Part 5: Questions

1. In Investigation 20, you learned that electric current was caused by the interaction of the elements of the circuit. Explain how the copper disc experiment and Edison's experiment led you to a new understanding of current.

2. You found in this investigation that like electrical charges repel each other. Explain how that finding led to the idea of potential energy difference between two points in an electric field.

3. You know that in solid conductors, negative charges move and positive charges do not move. A positively charged glass rod was held over the knob of an electroscope. Explain why the leaves separated.

4. Explain why the leaves of an electroscope separate when a negatively charged HR rod is held over the knob.

5. The reading you did on electric forces states that a real, measurable force is produced when charges repel each other. What data from this investigation prove that statement?

6. What is there about Edison's experiment that proves current is not a movement of positive charges?

7. The air in a room is very dry. You walk over a thick carpet and reach for a door knob. Just when your fingers are a few tenths of a centimeter from the knob, a spark jumps between your hand and the knob. You know a spark means that electricity is present. Where was the electricity before it jumped? How was the electricity generated? What kind of electricity is it?

8. The event described in this question occurs on the day following the event described in Question 7. It is raining outside. You walk up to the door and grasp the knob. No spark jumps between your hand. Explain why.

9. Tear a piece of paper into small pieces. Comb your hair for several seconds. Now hold the comb over the paper and observe what happens. Use what you know about rubbed rods and + and - charges and explain the actions you observed.

INVESTIGATION 22: ELECTRICITY AT REST

READING: EDISON'S EXPERIMENT

Thomas Alva Edison was an inventor who was born in the United States and spent his entire life developing materials to make life more efficient, easier, or more enjoyable. You probably use one of his inventions frequently. You call it a record player, stereo, or by some other name. In the past it has been called a talking machine, phonograph, and various other names. Thomas Edison, however, was the source of instruction for today's recorded music systems.

You probably know that another of Edison's inventions was the electric light bulb. His first bulb consisted of a glass container which contained a very high resistance material and from which the air had been pumped. Edison's first bulb (and bulbs for many years later) were as near a perfect vacuum as was possible to obtain. Pumping the air out reduced the probability of the filament oxidizing and thereby lengthening the life of the bulb. Not until some years later were bulbs filled with a gas that would not support the oxidization of the filament. Argon is a common gas used for that purpose. Edison conducted an experiment with the light bulb that helps solve the problem of whether current flows from + to - or - to +.

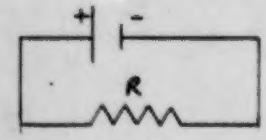
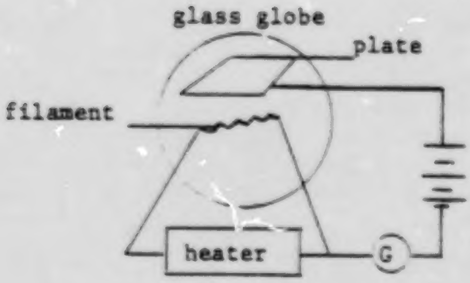


Figure 1

Look at Figure 1. You know that if resistance, R, is a wire, it will get hot. In fact, hooking a wire directly across an electrical energy source is called a short circuit (sometimes referred to as a dead short). You will destroy the dry cell quickly hooking it as show in Figure 1.

INVESTIGATION 22: ELECTRICITY AT REST



The wire used in a light bulb is very thin; it is called a filament. The filament in a light bulb gets white hot and gives off light. Edison placed a filament in a glass container as shown in Figure 2. He also placed a small metal plate in the container but did not connect it to the filament. Wires attached to the filament and plate stuck out through the glass globe. The air was then pumped out of the container.

Figure 2

Edison knew the electrical charges left a heated filament much more readily than they left a cold filament. (If you are interested in pursuing that idea look up thermionic emission in an encyclopedia or an advanced physics book.) So he put a heater across the filament. Next a battery was hooked between the filament and the plate. A galvanometer was also hooked into the circuit.

Notice in Figure 2 the negative pole of the battery is connected to the filament. So the filament is charged negatively. The battery's positive pole is hooked to the plate; the plate is charged positively. The filament is hot which loosens the electrical charges and makes their escape possible.

When the apparatus was hooked as shown in Figure 2, the galvanometer showed that a current was flowing through the space between the filament and the plate even though they were not connected. How could that flow of charges be explained? You know that like electrical charges repel each other and unlike charges attract each other. The heated filament in Figure 2 is charged negatively and the plate is charged positively. The negatively-charged filament, therefore, could have repelled negative charges from its heated surface which were then attracted to the positively-charged plate. Current, therefore, would be flowing from negative to positive. Keep in mind that the filament was hot.

INVESTIGATION 22: ELECTRICITY AT REST

You cannot know if the - to + model for current flow is correct until an experiment is done with the apparatus shown in Figure 2 to test the + to - possibility for current flow. Imagine that battery B is just reversed in Figure 2. Now the plate is charged negatively and the heated filament is charged positively. Edison also did that experiment. He found that the galvanometer showed that *no* current was flowing through the galvanometer. That means that no current moved through the space from the hot filament to the plate.

Now, *if* current had been movement of positive charges, as some believed, those positive charges would have been repelled by the heated positive filament and moved off the filament. They then would have been attracted to the negatively charged plate. *That did not happen*. Rather, a heated, negatively-charged filament repelled negative charges which were attracted to the positive plate. The data from Edison's experiment demonstrated that electric current is a movement of *negative* charges *not* positive charges.

The experiment you just read is called the *Edison Effect*. The Edison Effect, as was mentioned earlier, is also called thermionic emission. The *therm* portion of thermionic refers to heat and *ionic* refers to the charges that escape from the filament. Edison simply observed that thermionic emission occurred when the filament was heated and that current moved form - to +. He did not do anything with it. This effect, however, became the basis for the entire electronics industry. In order for that to occur, however, required that Lee DeForrest place a third element in the apparatus called a grid. He attached a negative charge to the grid which he could control and thus control the amount of negative charge that moved between the filament and the plate. That refinement on Edison's discovery led to radio, television, and all electronic devices. It was Thomas Alva Edison in 1883, however, who discovered the basic effect that now bears his name. Furthermore, he demonstrated that electric current moves from a negative source to a positive receiver. Positive charge does not move in a circuit like that shown in Figure 2. Positively charged ions do move through some liquids. But electrical circuits usually do not contain liquids and in them current moves from - to +.

READING: ELECTRIC POTENTIAL DIFFERENCE

You are really going to have to use your imagination while studying this reading because the objects we are going to use are isolated electric charges. Now an isolated positive (or negative) charge exists only in someone's imagination. It is only a mental model.

But mental models are often very useful in helping us understand what the real world is like. You know that you do not have to touch a charged rod to an electroscope's knob to get the leaves to diverge. Why is that true? The mental models you will build from what you will now read will help you answer that question.

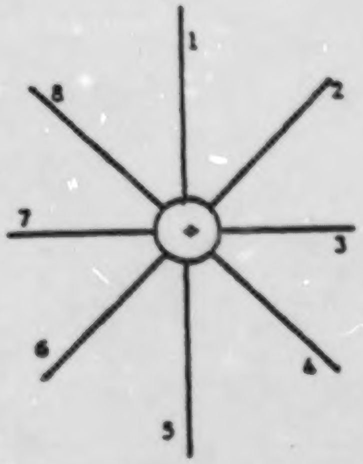


Figure 3

Imagine that you have an object that has a very high positive charge (that is possible) like that shown in the picture. Now suppose you had one small positive charge. (That probably exists only in your imagination.) Now imagine that you push the small positive charge (called a unit positive charge) along each of the lines, one through eight, toward the large positive charge. You know what is going to happen. The large positive charge is going to repel the unit positive charge and try to push it away on any of the lines, one through eight.

You also know that force of repulsion will not occur only when you reach the large positive charge. The unit positive charge is going to be repelled from whatever point you start on any of the lines and continue to be repelled all the way up to the large positive charge. (To find out about how large the force of repulsion is, read The Electrical Force-Distance Law.)

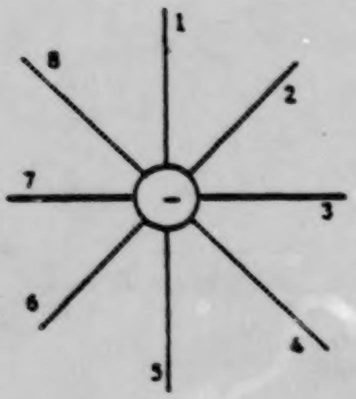


Figure 4

Now imagine that you have a large negative charge such as that shown in Figure 4 (that is possible). Once again you also have a unit positive charge. You are going to place the unit positive charge on lines one through eight. Here again, you know that the unit positive charge will be attracted to the large negative charge. That attraction will exist regardless of where the unit positive charge is placed on one of the lines.

So attraction between charges takes place not only when they touch but while one charge is in the area surrounding another. That area surrounding a charge in which another charge will experience repulsion or attraction is called the electric field of the charge.

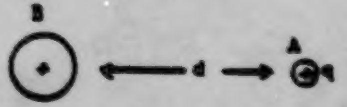


Figure 5

Study the diagram shown here. Point B represents the point at which a large positive charge is placed. A unit positive charge, +q, is placed at point A. Now if you were going to move +q from A toward B, you know that a force would be necessary because +q would be repelled by the large charge at B.

The force F_{AB}, pushing +q would be exerted over the distance, d, or a specific amount of work, W_{AB}, would be done. That amount of work is $W_{AB}=F_{AB}d$.

INVESTIGATION 22: ELECTRICITY AT REST

Think back to Investigation 19. There you learned that when work was done on an object, that object gained potential energy. If +q were released at B, it would return to A and use the potential energy it had gained in moving back to A. So $F_{AB}d$ represents the potential energy difference of +q between A and B.

An electric field surrounds the large positive charge placed at B. So point A is just one point in the electric field surrounding the large charge at B. The electric potential energy difference, W_{AB}, per unit of positive charge, +q, is called the potential difference, V_{AB}, or $V_{AB}=W_{AB}/q$. So V_{AB} between A and B is the work done per unit charge in slowly moving a unit charge +q from A the point of lower potential energy to B, the point of higher potential energy.

Suppose +q had zero potential energy at point A. Then in moving it to point B, its potential energy would be $W_{AB}-0=W_{AB}$. Or another way to look at that situation is that every point in a field has the potential of giving a charge a certain amount of energy if we consider the charge has zero potential energy at that point. That quantity is referred to as electric potential, but it is associated with a particular point in an electric field.

Suppose that W_{AB} is measured in joules and q is measured in coulombs. Then

$$V_{AB}=\frac{W_{AB}}{q}$$

$$=\frac{\text{joules}}{\text{coulomb}}$$

$$=\text{volts}$$

So a 12 volt battery, V_{AB}, can be thought of as being capable of providing an electrical charge of one coulomb, q, with 12 joules of energy, W_{AB}, while that charge is moving between the terminals of the battery in an external circuit.

INVESTIGATION 22: ELECTRICITY AT REST

Now that you know exactly what a volt is, you may also be interested to learn what an ampere is: the ampere, of course, is the unit you have been using to describe current in an electric circuit. You now know that electric current is a movement of negative electric charges, so it is reasonable to assume the ampere measures something about charges. One ampere is the amount of current when one coulomb of charge (equivalent to about 6.0×10^{18} electrons) moves past a specific point in the circuit every second. So the ampere then has units of coulomb/second.

THE ELECTRICAL FORCE-DISTANCE LAW

One of the first observations made about static electricity was that charged objects or one charged object and an electrically neutral one seemed to be attracted to each other. Newton had already established the Universal Law of Gravitation which says that the attraction between objects varies inversely with the square of the distance between them. A natural extension of Newton's gravitational law for early experimenters was to hypothesize that the force between two objects at least one of which was electrically charged varied inversely with the square of the distance between them. Some time in the late 18th century, Daniel Bernoulli placed an electrically-charged metal disk various distances from an uncharged metal disk and measured the force of attraction between them. Bernoulli's data showed that the force between the two objects he used and which attracted each other electrically does vary inversely with the square of the distance between them. Approximately ten years later, a United States citizen who was living in England, Benjamin Franklin, and the discoverer of oxygen, Joseph Priestly, verified the findings of Bernoulli.

Around 1770, another Englishman, Henry Cavendish, did an experiment similar to Priestley's. Cavendish, however, added another dimension to his experiment which came from the work Newton had initiated with gravitation. Newton had inferred in the Principia, that the gravitational force on an object enclosed in a hollow sphere is zero if the body is spherical in shape and has walls of uniform density. The similarities of electrical force between charged objects led Cavendish to suspect that using spherical charged objects might lead him to prove the inverse-square relation for electrical forces. He was successful.

The experiments of Priestly and Cavendish provided qualitative evidence that the inverse-square law was applicable to forces between charged objects. What was needed was a direct experiment that used spheres and in which forces would be measured just as Bernoulli had.

In France in 1785, Charles Augustin Coulomb (1736-1806) carried out such a direct experiment and he used spheres as the carriers of the electrical charge. Before 1785, Coulomb had been interested in what happens to metal rods and wires when they are twisted. To carry out his studies he built a torsion balance which has a wire or rod clamped solidly at one end (see Figure 1).

INVESTIGATION 22: ELECTRICITY AT REST

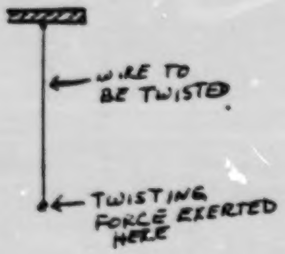


Figure 1. The Torsion Balance

A known amount of twisting force is applied at the opposite end of the rod and that twisting force tends to rotate the rod. Coulomb used his torsion balance to measure the relationships among the variables of electric charge, distance and force. He must have hypothesized that the forces he was going to measure would be small because he used a rather fine wire in the torsion balance. He made other adjustments on his torsion balance as shown in Figure 2. A light horizontal rod of poorly conducting material is perpendicular to the fiber which is twisted. That horizontal rod has pith balls fastened to each end. Those balls can turn in a circle as shown in Figure 2.

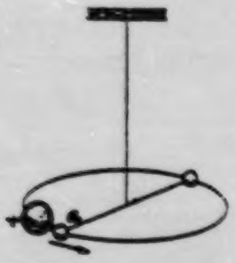


Figure 2

A second pith ball t is rigidly mounted in a position close to the movable ones. When both balls "t" and "a" are given electric charges of the same sign, either + and +, or - and -, the balls repel each other, causing the horizontal rod to rotate until the elastic restoring force set up in the twisted suspension fiber is sufficiently large to counter-balance the effect of the electrical repulsion. Since Coulomb knew from his earlier elastic studies that the angle through which the suspension fiber is twisted is directly proportional to the twisting force applied to the ball on the end of the horizontal rod, he now had a way of computing the force from the observed angle of rotation. Coulomb's torsion balance was so sensitive that he could measure a ten-thousandth of a gram of force which is a force of $6x10^{-8}$ newtons.

INVESTIGATION 22: ELECTRICITY AT REST

Coulomb enclosed the twisting wire, the rotating balls and the stationary ball in a container. The electrical charge was placed on the small ball *a* and ball *t* in Figure 2 by attaching a pin to an insulating handle and placing electrical charge on the pin. The charged pin was then passed through a hole on the top of the container which was covering the rotating balls and ball *t*.

From his measurements, Coulomb proved conclusively that the force, F, of attraction or repulsion between two spherical objects varies inversely with the square of the distance, d, between their centers. Or:

$$F \propto \frac{1}{d^2}.$$

Coulomb had no way of exactly measuring the amount of charge he put on the spheres; he could only estimate those amounts. Through much experimentation, he concluded that the force, F, between charged objects also varied *directly* with the product of the amount of charge, Q, on each. Or:

$$F \propto \frac{Q_1Q_2}{d_2}.$$

The proportionality just stated is made an equality by introducing a constant which reflects the medium in which the measurement is made. For a vacuum or air, that constant is one. Although Coulomb could not exactly measure the amounts of electrical charge he was using, his estimates must have been quite accurate because by using modern apparatus, the equation $F=k(Q_1Q_2)/(d_2)$ can be verified. That equation is known as Coulomb's Law.

Writing in the March 8, 1957, edition of *Science* magazine, J.R. Zacharias said:

> "Like charges repel, and unlike charges attract each other with a force that varies inversely as the square of the distance between them...in *all* of atomic and molecular physics, in *all* solids, liquids, and gases, and in *all* things that involve our relationship with our environment, the *only* force law, besides gravity, is some manifestation of this simple law. Frictional forces, wind forces, chemical bonds, viscosity and magnetism, the forces that make the wheels of industry go around—all these are nothing but Coulomb's law..."

That statement gives you some idea of the importance of the electrical force-distance relationship.

Name________________________

Section______________________

Introduction

In the last three investigations you have been working with currents and voltages. You have been told that the voltage of a cell is a measure of its energy. An electric current has been defined as the result of the interaction among the circuit elements. In this investigation, you are going to be given data that was gathered by using apparatus. Those data will permit you to probe behind the definitions of current and voltage you havedoes a dry cell give energy? ?During this investigation you will build some mental models that may help you answer those questions.

Equipment

The data you will be given were gathered by using specific apparatus. That apparatus is called an electroscope. Two different types of electroscopes are shown in Figure 1. Your instructor will also show you an electroscope. The principal parts of the electroscope are the thin metal leaves which hang freely at the end of a metal rod or next to a solid metal rod.

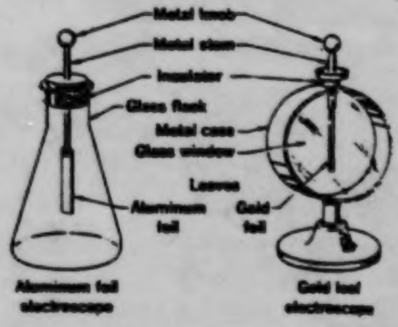


Figure 1

The metal rod has a spherical knob on the end extending outside the electroscope. The case of the electroscope is metal or glass and is needed to keep the air flowing by the metal leaves to a minimum. The metal rod is held away from the case by an electrical insulator. In the aluminum foil electroscope in Figure 1, the case is a glass Erlenmeyer flask and the electrical insulator is a rubber stopper.

In the gold leaf electroscope, the front and back of the case are glass plates, but the circular sides are metal. Insulators for those electroscopes are usually plastric; cork, rubber, glass and wood are also used sometimes. The purpose of the insulator is to keep any electricity on or in the metal rod from passing to the case. All the electricity used in an electroscope is kept on or in the spherical metal knob, the metal rod and the metal foil leaves.

A hard rubber (HR) rod, a glass rod, a piece of silk and a piece of wool were also used in gathering the data. Also a special disc-and-rod made from copper was used. The disc is 5 cms. in diameter and a rod 10 cms. long was soldered perpendicular to its exact center. That apparatus is shown in Figure 2.

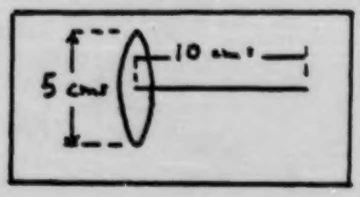


Figure 2

Exploration: Part 1

A. An HR rod was rubbed vigorously with a piece of wool and held near but not touching the knob of an electroscope. The electroscope's leaves moved apart--diverged--at their free ends. When the HR rod was moved away, the leaves moved so they were hanging straight down--they collapsed.

B. An HR rod that had not been rubbed with wool was held over the electroscope's knob and the leaves did not move. A glass rod was held over the electroscope's knob and the leaves did not move.

C. The glass rod was rubbed with silk and held near but not touching the electroscope's knob. The electroscope's leaves diverged and when the rod was removed, they collapsed.

1. Write an interpretation of the data given in A, B, and C.

D. Before each of the following experiments was done, the leaves of the electroscope were hanging straight down and had the normal amount of separation between them.

E. The experimenter touched HR and glass rods that had not been rubbed to the electroscope's knob. Nothing happened in either case to the leaves of the electroscope.

F. A glass rod was rubbed with silk and touched to the electroscope's knob. The leaves diverged and when the glass was removed the leaves stayed diverged.

IMMEDIATELY after the glass rod was removed from the electroscope's knob, an HR rod that had been rubbed with wool was touched to the knob. The leaves collapsed and then immediately diverged again and stayed that way.

2. Write an interpretation of the data given in D, E, and F.

The Idea

While both rods make the leaves diverge, they do it in an opposite way because the leaves collapsed when the HR rod was touched and then diverged again. You know that the metal leaves of the electroscope have weight. A force, therefore, is necessary to move them, and the data you were given told you the leaves moved. The movement occurred when the rubbed rods were brought near the electroscope's knob and when the knob was touched. Something about rubbing the rods permitted them to generate a force great enough to move a weight. In other words, the rubbed rods gave energy to the electroscope's leaves.

3. Using the idea of work, explain why the last statement is true.

The energy used in lifting the electroscope's leaves began with the rubbed rods. When the rods were rubbed, they gained an

ELECTRICAL CHARGE.

That electrical charge was responsible for producing a force that caused the leaves to move.

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Expansion of the Idea

How can the electrical charge or the rubbed rods be responsible for generating a force that will cause the electroscope's leaves to separate? To answer that question, carefully study the interpretation you wrote in Question 2.

4. An interpretation can be stated as a rule. Write that rule here.

5. In the space below, justify why your rule is proper. You may wish to review the data given in Question 2 and the interpretation of those data you wrote in Question 2.

There are two kinds of charge and they are opposite to each other. Because of their oppositeness, charges have been named positive (+) and negative (-). When an object has equal numbers of positive and negative charges, it is electrically neutral. All non-charged objects are neutral.

In the first portion of this investigation, the data you were given told you that just holding a charged rod near the knob of the uncharged electroscope caused the leaves to move. In other words, force enough to do the work of lifting the leaves was generated. Objects can be electrically neutra. You also know the rule about attraction and repulsion of charges.

6. Combine those ideas and explain why just bringing a charged rod near the electroscope's knob causes the leaves to separate.

Name________________________

Section_______________________

Exploration: Part II

In the first portion of this investigation, you found that an object can be charged and the charge stays there. Touching a charged rod to the knob of an electroscope charged the leaves and caused them to diverge. Those leaves remained diverged for some time. In other words, the charges on the leaves were at rest or static. That area of physics that deals with electrical charges at rest is called static electricity. A cloud stores electrical charge until it cannot hold any more. Then the cloud gives (discharges) its charge to another cloud or to the earth. When the charged cloud discharges to the earth, lightning has struck. Now evaluate the probable accuracy of the saying "lightning never strikes twice in the same place."

In the equipment section of this investigation, a special copper apparatus was described in Figure 2. An experimenter assembled it as shown in Figure 3. The aluminum foil hangs freely in front of the copper disc, but is not attached to it.

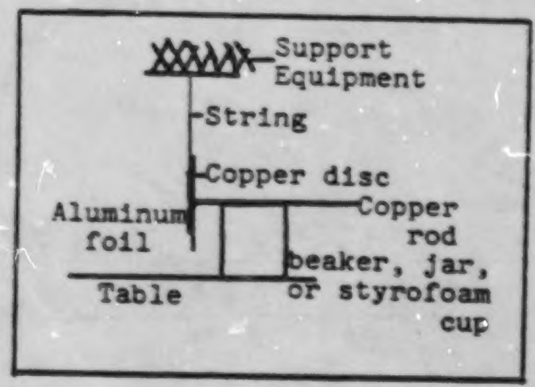

Figure 3

The HR rod was rubbed along the copper rod but was not touched to the copper disc. The aluminum foil did not move. The HR rod was then charged by rubbing it with wool. It was then rubbed along the copper rod but not allowed to touch the copper disc. The aluminum foil moved to about a centimeter in front of the disc and remained there.

7. What happened to the aluminum foil?

The experimenter then placed a finger on the copper rod and the aluminum foil moved back against the copper disc. Because the aluminum foil moved back against the disc, the action of the experimenter removed the charge from the disc. That process is called grounding. The glass rod was rubbed with the silk and touched to the copper rod but not allowed to touch the copper disc. The aluminum foil again moved away from the copper disc.

The Idea

Remember, the charged rods were touched to the copper rod only and were not allowed to touch the disc. In other words, the electrical charge from the rubbed rods was placed on the copper rod not on the copper disc. Yet the evidence says that the copper disc was charged.

8. Explain how the electrical charge got from the copper rod to the copper disc.

The movement of charges along the copper rod is called an

ELECTRICAL CURRENT.

9. What would be a suitable name for a material--such as the copper rod--that allows current to move through it?

An electrical current is a movement of electrical charge.

Expansion of the Idea

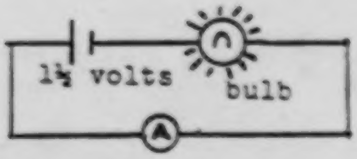

Figure 4

10. Connect the circuit shown in Figure 4. Use the ideas of electrical charge and current and write an explanation of why the bulb lights. Be sure to use the terms electrical charge and electrical current in your explanation.

Your instructor will now set up the circuit shown in Figure 5 and do a special demonstration for you.

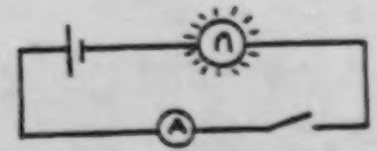

Figure 5

11. When compared with the circuit in Figure 4, what did the special demonstration show?

12. In the introduction to this investigation, this question was asked: "What does a dry cell give energy to?" Go back to the statement made about current and electrical charge in The Idea and write an answer to that question below.

13. Combine what you just wrote with the results of Edison's experiment. What type of electrical charges does the dry cell give energy to?

14 .That type of charge has a special name. Write it here.

To develop a complete understanding of the relationship between energy and electrical current, you need to do some reading. Go to the reading, Electrical Potential Difference, and complete it.

Name____________________

Section____________________

Introduction

You have had all kinds of experiences with magnets. You know they pick up certain kinds of metal. What kinds will they attract? What types of metal will they not attract? Perhaps you should conduct an investigation to find out. If you investigate the types of metal magnets attract, be sure to keep accurate records. You know magnets will not attract glass, wood, string, plastic and a lot of other things. Two magnets will stick together. That you already know. But, maybe you do not know why. This investigation will help you find out why and lots of other information about magnets.

Exploration

The data you need for the first part of this investigation should be gathered out-of-doors. Keep away from buildings, fences, schoolground equipment, flag poles or any other objects. You should be in the center of a circle that has a diameter of about three meters.

1. Tie a piece of string around the middle of a bar magnet. Adjust the string until it holds the magnet parallel with the ground. Hold the string and observe what the magnet does. Repeat that action several times. Record your observations.

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2. Each end of the magnet is called a pole. A magnet has two poles. Use what you know about geographic directions and give each end of the magnet a name. Record those names and why you selected them here.

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Mark the ends of your magnet so you will know which pole has which name. Return to your classroom.

You need two magnets for this part of the investigation.

1. Hold a magnet in each hand. Now very slowly move the poles on the ends of the magnets toward each other. What do you observe? Repeat the experiment if necessary.

2. Now turn one of the magnets around. The pole of that magnet that was not facing the pole of the magnet in the other hand should now face that pole. Move the poles of the magnets together very slowly. What do you observe? Repeat the experiment if necessary. Record your observations from the two experiments you just completed.

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The Idea

Discuss with the members of your laboratory group the observations you made during the experiments with the two magnets. Your group should develop a rule which explains how the poles of magnets affect each other. Record that rule here.

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Name______________________

Section______________________

Expansion of the Idea

Part 1: An Experiment

1. Lay a bar magnet on a table. Be sure it is far away from any metal that might be in the table. You next need a compass. Place the compass on the table about 50 cms from one pole of the magnet. Slowly move the compass toward one of the magnet's poles. Observe what the compass needle does. Record your observations below.

2. Now move the compass toward the opposite pole of the magnet. Observe what the compass needle does. Record your observations.

3. Now replace the compass with a steel nail. Carefully move the nail toward each pole of the magnet. Record your observations.

4. How was the behavior of the nail different from what the compass did when moved toward the magnet?

5. Based upon your experiments with the bar magnet, the compass, the nail, and the rule you made about magnet poles, what is the compass needle?

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6. Give a thorough description of the evidence you have to support the answer you just gave.

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7. Use the evidence and rule you have about magnetic poles and predict which end of the compass needle should point north. Now test your prediction. If your prediction was correct, explain why it was correct.

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If your prediction was not correct, explain in the blanks above why it was not correct.

8. Once again place a bar magnet on a large piece of paper which has been placed on a level, flat surface. Be sure there is no metal close to the magnet. Move the compass very slowly toward one end of the compass. Watch the compass needle very carefully. The instant the compass needle moves, stop moving the compass. Mark that spot on the paper. Also, draw a line which represents the compass needle. Be sure to indicate which end of the line represents which end of the compass needle.

Now move the compass to the opposite pole of the magnet and repeat the experiment just completed. Next move the compass in toward the middle of the magnet from each side. Select two other points between each pole and the middle of the magnet and on each side. Repeat the procedure of moving the compass toward the magnet.

When you have finished, you should have moved the compass toward the magnet from twelve different points. You should have an area around the magnet marked out by twelve separate points. At each of those points, you should have drawn a line representing which way the ends of the compass needle pointed. Be sure you know which end of each line represents which end of the compass needle. Be sure to save this diagram and remember which bar magnet you used.

The area you just mapped is called a magnetic field. It has some special properties. Anywhere on or within the boundary of the magnetic field, the interaction between it and a compass needle produced enough force to move the compass needle. What evidence do you have that supports the statement that the magnetic field-compass needle interaction produced enough force to move the compass needle?

9. You found that a magnet will attract a small steel nail. Did the nail stick to the magnet only after touching it, or did the nail move toward the magnet? The following experiment will help you develop an answer to that question.

   a. Place the magnet in the center of a flat surface which has no metal near. Move the small steel nail, thumbtacks, iron fillings, paper clips and other small, very light-weight steel objects toward the magnet. Record your observation.

   b. Now answer the question asked about the nail and the magnet asked above.

10. The interaction between some objects and the magnetic field produces a force which causes the compass needle to move in a circle and steel objects to move toward the magnet. When a force causes an object to move a distance, what has been done on that object?

11. What does your answer to Question 10 tell you about a magnetic field?

12. Examine the lines you drew on the paper which represented the position of the compass needle as you moved it around the magnet. What do those lines tell you about a magnetic field?

13. You know that a magnetic field surrounds a bar magnet. But, what does a magnetic field look like? You also know that magnetic fields interact with iron. You can use that interaction to obtain a picture of a magnetic field.

    Place a piece of glass or a stiff piece of paper over the same bar magnet you used to outline the magnetic field using the compass. Very slowly sprinkle iron filings over the paper (or glass). If the filings fall in bunches, gently tap the paper (or glass). Give the iron filings every opportunity to be captured by and interact with the field of the magnet. When the filings are settled, draw a diagram of the magnetic field inside of the boundaries you established for it earlier.

Measure how far out from the magnet its field affects iron filings. Now measure, from the same point on the magnet, how far out the field of the magnet influenced the compass needle. Compare the two mappings of the magnetic field you have made. Record your comparison below.

You may wish to orient two or more magnets near each other and repeat the iron filings procedure. Be sure to diagram the results and try to explain why you obtained the patterns you did.

Draw a diagram of the magnetic field of your magnet in the space below.

Name____________________

Section____________________

Expansion of the Idea

Part 2: Readings Questions

1. Write a definition of a magnetic field. Support your definition with evidence found in the investigation.

2. Write a description of why a force moving an object through a distance in a magnetic field is important.

3. You know that magnetic poles interact with each other. One pole of a magnet points north and the other south. What does that allow you to say about the earth? Remember, you must base your answer on the evidence you collected in this investigation.

4. Give an explanation of what isogonic lines are.

READING: THE EARTH AS A MAGNET*

Proofs of the Earth's Magnetism

The behavior of the compass needle indicates that the earth itself is a great magnet. Magnetic oxide of iron in some deposits in the earth is found to be magnetized. Natural magnets of this material are called lodestones. Compass needles show the direction of the lines of magnetic force of the earth.

While the magnetic field of the earth is weak compared with that near a permanent magnet, these experiments show that it does exist. Steel umbrella rods, vertical steel pipes, girders, and machine tools are usually found to be permanent magnets, as the result of the inductive effect of the earth's magnetism. Their N poles are always at the bottom in the northern hemisphere. We may then conclude that the earth acts like a spherical magnet with two poles, one in the Northern and one in the Southern Hemisphere. According to the naming we have adopted for compass poles, the earth's pole in the Northern Hemisphere must be a S pole, and that in the Southern Hemisphere a N pole, but they are not so named.

Declination

If a compass is observed outdoors on a starry night, it will be found that in most places it will not point directly at the North Star, but may point more than 20° west of it in Maine or 20° east of north in Oregon. This shows that the magnetic lines of force of the earth do not run north and south. The angle between the direction of the needle and a north-south line at any place (Figure 1) is called the variation or declination at that place. Very careful determinations of declination are constantly being made by the various governments of the world and recorded on maps and charts for the use of surveyors and navigators, since without this information compass directions would be very misleading.

Figure 2 shows lines that connect places of equal declination for the United States. These lines are called isogonic lines, and the line of no declination is called the agonic line. Voyages before the time of Columbus had been so short and so near the agonic line (as it then was) that the compass was believed to point due north. Columbus must have been much disturbed to discover a change (from 3°W to 11°E) in the direction of his compass as he sailed westward on his long trip.

INVESTIGATION 23: MAGNETISM

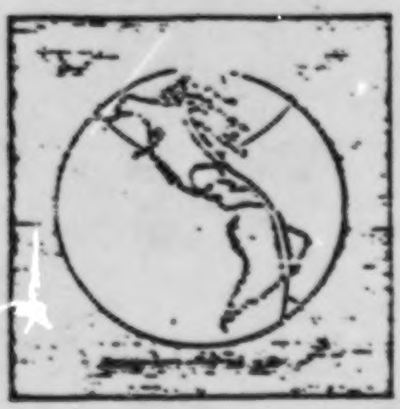

Figure 1: Compass Declination. The compass points exactly north only when placed on the agonic line. Both compass arrows point to the magnetic (not geographic) pole.

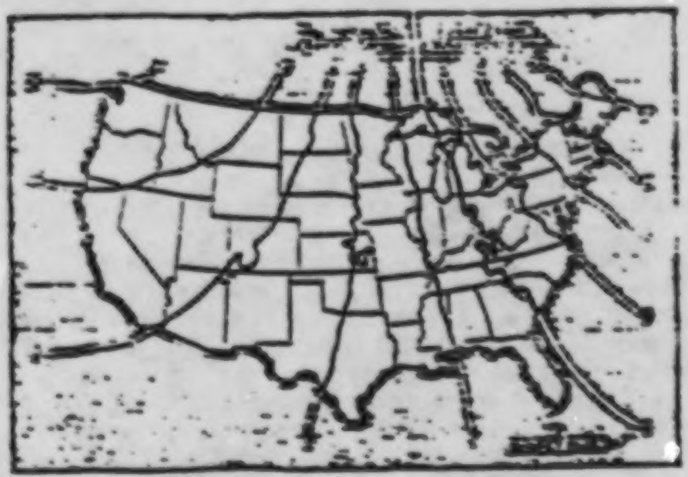

Figure 2: Isogonic Lines in the United States. The agonic line is marked 0-0. Note the great difference in declination in different parts of New York State.

- Taken from Robert W. Fuller, Raymond B. Brownlee, D. Lee Baker, Elements of Physics, Allyn & Bacon, 1948, pp. 559-562. Used with permission.

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READING: EARTH'S MAGNETIC FIELD*

If we use a compass needle to map the magnetic field on a bare table, we find ourselves drawing a set of parallel lines running roughly north and south. A suspended bar magnet, free to turn, will set itself along the same direction--it is just a giant compass needle. This set of n-s lines is the magnetic field that is still there when we have removed all magnets. Exploring over the face of the Earth, we find that the lines seem to converge towards a region in northern Canada and another region in Australia. In most places, the lines are not horizontal, but slant down into the ground.1 Their pattern suggests that the Earth behaves like a vast bar magnet with its magnetic axis slightly tilted from the geographical spin-axis (Figure 1). It is the Earth's weak field that is used for navigating by compass, though a steel ship adds its own magnetic field--part of it a changeable field, too--to confuse matters.

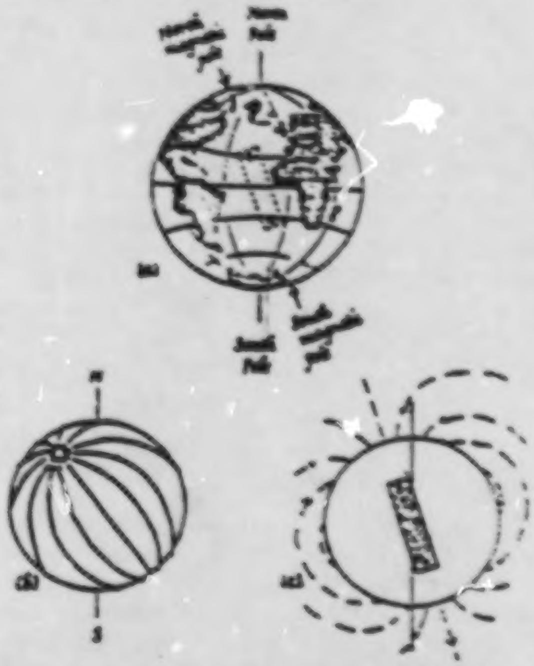

Figure 1. The Equivalent Magnet for the Earth's External Magnetic Field. (a) Earth and equivalent magnet. (b) Lines of magnetic field along the Earth's surface (These show the direction, but not the strength, of the horizontal component of the Earth's magnetic field.) (c) Lines of the Earth and its magnetic field, shown in section.

INVESTIGATION 23: MAGNETISM

The North-seeking pole of a compass points towards northern Canada. Therefore, the Earth must have a South-seeking type of pole there. (The Earth's pole there is sometimes called the North Magnetic Pole. If you find this confusing, avoid the abbreviations such as N-pole and describe all poles by their full names, such as North-seeking pole, and you will find no paradox. When you have cleared up your thinking on this, you may find it saves time to return to the abbreviations.)

The Earth's magnetic field is uniform, constant in strength and in direction, over wide regions. It therefore provides a very important test, to see whether the N and S poles of a magnet are equal. Float a magnet on a cork in water. The Earth's field pulls it to point N-S. If the floating magnet's N and S poles are equal in strength (though opposite in kind) we should expect the pulls of the Earth's uniform field on them to be equal. Such pulls would twist the magnet around, but would not move it Northward across the pool of water or in any other direction. If the floating magnet's poles are not equal, we should expect unequal pulls to move it in some direction. Try this important test.

Though the Earth's magnetic field is weak, it can bend the path of electron streams appreciably. You will see in a later section how a magnetic field pushes an electric current sideways with a catapult force. The streams of charged particles in cosmic rays come flying into the Earth's magnetic field from far away in space and are swung around by it. Experiments are being made now which use the Earth in this way as a giant control magnet for cosmic rays.

[1] In most parts of the United States, the Earth's field dips steeply down into the ground, at angles like 70° with the horizontal. A magnet free to follow it should point along this slanting direction. Why does an ordinary compass needle remain horizontal and not slant thus? Its pivot certainly would not prevent it from slanting--we ought to see the N pole of the needle scraping on the bottom of the compass box. If you guess the correct answer to this puzzle, you will see that there is a simple experimental test of your guess and you should apply for the necessary apparatus and try the test.)

* Taken from Eric M. Rogers, Physics for the Inquiring Mind, Princeton University Press, Princeton, N.J., 1960, pp. 572-573.

INVESTIGATION 23: MAGNETISM

READING: MAGNETS AND MAGNETIC FIELDS*

Knowledge of magnets and their effects had been accumulating for centuries and gradually grew into a quite separate branch of physical sicence called magnetism. We shall be content here merely with summarizing some basic phenomena and concepts of magnetism that are pertinent for our purposes.

1. Lodestones are naturally occurring magnets; they usually consist of the black oxide of iron called magnetite (Fe_3O_4).

2. A few substances such as steel and certain alloys of metals become fairly permanent magnets after having been held for some time close to a lodestone. Soft iron is magnetized only while near a magnet.

3. If a bar magnet is dipped into iron filings, the filings tend to cling to it at certain places more than at others; these regions are usually at opposite ends of the magnet and are called magnetic poles.

4. If a magnet is suspended horizontally by a thread or floated on a cork in water, it will rotate until one pole points northward and the other pole southward. The north-seeking pole is called simply the north pole or N-pole; the pole at the other end is the south pole or S-pole. These poles always occur in pairs of opposite sign. While it is impossible to make a magnet with only one pole, a single pole may be effectively isolated for study by using a long thin magnet, so that one pole is remote from the other.

5. Poles of like sign repel each other; those of unlike sign attract each other.

6. Coulomb studied the forces between magnetic poles and arrived at the Coulomb magnetic force law: the force F between two magnetic poles of pole strengths p_1 and p_2 is directly proportional to the pole strengths and inversely proportional to the square of the distance r between them, or $F \propto p_1 p_2/r^2$. This relation may be used to define a unit of magnetic pole strength p, much as we used the eletrostatic force law (Investigation 22) to define a unit of electric charge q. To cast the last proportionality into an equation, we write

$$F = k\frac{p_1 p_2}{r_2}$$

here the constant k (Greek Kappa) is 6.35×10^{10} N·m^2/(unit pole)^2 in the system of units used in this book.

* Taken from Gerald Holton and Duane H.D. Roller, Foundations of Modern Physical Science, Addison-Wesley Publishing Co. Inc., Reading, Mass, 1958, pp. 517-518. Used with permission.

INVESTIGATION 24: CURRENTS AND MAGNETISM STUDENT GUIDE

Name________________________

Section______________________

Introduction

In the last four investigations you have worked with current electricity, static electricity, and magnetism and magnetic fields. You found that when electrical charges move they cause a current. There is, in other words, a relationship between static electricity and current electricity. Magnetism, however, has so far been studied by itself. In this investigation you will explore whether or not electricity and magnetism are related.

In this investigation you will use a galvanometer; you have not used one before. A galvanometer is a device that measures the presence of very small amounts of current. Do not try to make sense out of the name *galvanometer*. You know that *to meter* something is to measure it. Following that line of reasoning, a galvanometer measures *galvans*. Do not be misled. There are no *galvans* in physics. The galvanometer was named for a 18th century Italian physician Luigi Galvani (1737-1798). Galvani discovered that electricity effects muscles. That finding is an important part of the science of neurophysiology. You will notice that the *0* marking on the galvanometer's scale is in the exact center. That means that this instrument can detect current going through it from either direction. Be sure your instructor approves any circuits you use involving a galvanumeter before you close the switch. The symbol for the galvanometer is (G).

Exploration

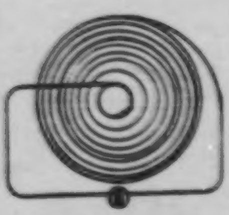

Figure 1

Connect the wire coil to the galvanometer as shown in Figure 1. Push the north pole of a bar magnet into the coil.

1. What happens to the galvanometer needle?

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2. How does the speed with which you move the magnet affect what you observe?

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3. Use the magnet and the galvanometer to determine what happens in each of the following instances. You may use the galvanometer needle to describe your observations. To control the variable of how the magnet is pushed into the coil of wire, insert it into the left end of the coil.

   a. North pole pushed into the coil ________________

   b. North pole pulled out of the coil ________________

   c. South pole pushed into the coil ________________

   d. South pole pulled out of the coil ________________

   e. Try several of the cases listed above with the magnet stationary and the coil being moved. What differences and similarities do you find when compared to the results of Questions a through d?

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4. What effect does using two magnets have on your observations? (Try using them with unlike poles together and with like poles together.)

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5. Now increase the number of turns of wire in the coil. Be sure all the wire is wound into the coil in the same direction. What effects do you observe by increasing the number of turns of wire found in the coil?

The Idea

You, your classmates, and your instructor should now form a statement that explains what the data just collected mean. Remember, you have to consider galvanometer readings, magnets moving through coils of wire and the number of turns of wire in the coil. Your statement needs to account for all of those factors.

Name________________________

Section______________________

Expansion of the Idea

Part 1: Experimenting

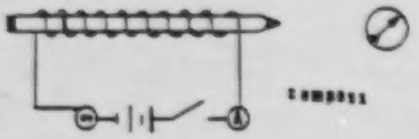

Figure 2

Study Figure 2. The wire is wound around a pencil. The lightbulb is in the circuit to help control the current which can be read on the ammeter. Be sure your instructor approves your circuit before closing the switch.

1. Close the switch and move the compass close to the coil of wire. What do you observe?

2. Move the compass all along each side of the coil. Watch the compass needle. Record your observations.

3. Now move the compass to one end of the coil and then the other end. What do you observe?

4. Now open the switch in the circuit. Move the compass all around the coil and to each end. What did you observe?

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5. What did the current in the coil do to the coil of wire?

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6. You, your classmates, and your instructor need to make a statement about what the actions you just observed mean. You observed those actions when current was flowing in the circuit and when it was not flowing. What do the actions of the compass needle show?

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7. So far in this entire investigation you have found two important principles about the relationships between electricity and magnetism--or electromagnetism. List those principles here.

a. ______________________________________

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b. ______________________________________

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8. You know that current flows from the negative pole of the battery of cells to the positive pole. Imagine that you would grasp the wire coiled around the pencil with your left hand. Imagine the pencil laying in the palm of your left hand. Curl your fingers around the pencil in the direction the current is moving. Extend your thumb to make a right angle with your index finger. What does your thumb point to on the coil?

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8. How could you test your answer using a compass?

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Study Figure 3, then put the circuit together at your laboratory table. Have a laboratory partner hold the long, straight portion of the wire above the table so a compass can be passed above and below it.

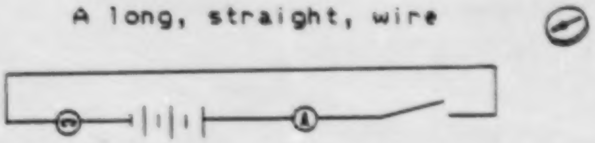

Figure 3

9. Move a compass along the entire length of the wire on both of its sides, that is above and below it. Move the compass around the wire in vertical circles. Record your findings.

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10. How does what you have found here compare with what you found when you tested the coil wound around the pencil with the compass?

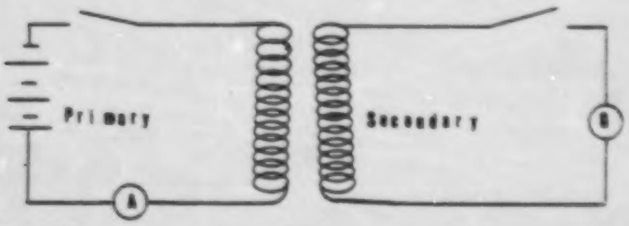

Figure 4

Figure 4 shows two coils of wire that are not connected. The primary coil is connected to a power supply. (Dry cells are not satisfactory for this experiment.)

11. Study the figure above, then set up the circuits at your laboratory table. Adjust the power supply until approximately 0.5 ampere flows in the primary coil. Be sure to record the value of the current in the primary coil and open the switch. Close the switch on the secondary coil and make sure the galvanometer is properly connected. Observe the galvanometer very carefully and close the switch in the primary circuit. Record what you observed. (Current in primary coil ______ amperes)

12. Wind the primary coil around a slender iron rod and repeat the experiment. Record your results. What explanation can you give for your findings?

13. Wind the secondary coil around the other slender iron rod and repeat the experiment. How are these results different from the last two results? How would you explain your results?

14. Do further experiments by changing the number of turns in the secondary coil and then the primary coil. Record how those actions influenced the results.

15. You have just experimented with a transformer. A transformer uses a magnetic field to produce an electrical current in the secondary coil. You know that either the coil or the magnetic field must be moving to produce a current in the coil. Think about when the galvanometer told you there was a current in the secondary coil. Using that information, when is the current in the secondary coil generated?

Name____________________

Section____________________

Expansion of the Idea

Part 2: Questions and Problems

1. The poles are not labeled on the magnet shown in Figure 5. When it is pushed into the coil of wire, the galvanometer needle moves in the direction of the arrow. Label the poles of the magnet.

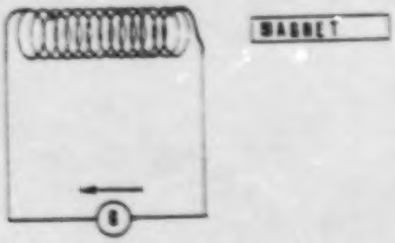

Figure 5

2. A coil of wire is to be wrapped around a steel nail. The right end is to be the north magnetic pole. Draw a diagram showing how the battery must be connected and how the wire must be wound around the wire.

3. An electric generator has huge coils of wire which are moved rapidly through a magnetic field. Explain why all electricity from a generating plant begins with some type of fuel.

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4. An automobile engine works because an electric spark is produced in the spark plug gap igniting the fuel in the cylinder. That electricity comes from the car's battery. The battery does not run down because a generator continues supplying electrical energy to it. There is a belt running from the engine drive shaft to the generator.

a. From your study of Investigation 24, explain how the generator must work.

b. What supplies the energy to run the generator?

5. In a step up transformer, a voltmeter and an ammeter in the primary circuit indicate 2300 volts and 300 amps respectively. With 500 turns in the primary side and 100,000 turns in the secondary, what will be:

a. The voltage?

b. The current of the secondary, neglecting losses?

Name____________________

Section____________________

Expansion of the Idea

Part 3: Readings Questions

1. Electric meters are possible because of a particular property of electric currents. What is that property?

2. What are the necessary parts of a galvanometer?

3. Any electric meter has a rotating coil. What force rotates that coil? Prove that all the necessary parts of the galvanometer interact to produce that force.

4. How is a voltmeter different from a galvanometer?

5. How is a voltmeter different from an ammeter?

READING: MAGNETS*

Making Magnets

In modern practice, electric currents are used to magnetize magnets. The current is not sent through the bar to be magnetized, but *around* it in a coil of wire around it. The magnetic field inside a long cylindrical coil (a *solenoid*) is uniform, and it can be varied from very weak to very strong by increasing the current, so it provides a good field for experimenting on making magnets. We place a steel bar inside a solenoid, turn on a current through the coil and find that, while the current runs, the bar is a magnet. When the current is switched off, the bar remains a magnet, though not such a strong one. The current needs to run for only a very small fraction of a second to produce its full effect. There are several good materials for such *permanent* magnets. Most hardened steels are fairly good. Special steels containing tungsten or cobalt are better, while some new alloys containing aluminum, *Alnico*, make stronger magnets still, though they need big fields to magnetize them. All these can be magnetized by being placed in a magnetic field for a short time. Reversing the magnetic field, by reversing the current in the coil, reverses the magnetization.

Demagnetizing Magnets

We can demagnetize a bar completely by placing it in such a coil carrying alternating current and then slowly taking it out and away from the coil. Or we may slowly reduce the alternating current to zero, with a rheostat.

Temporary Magnets, Soft Iron

When we attempt to magnetize a piece of soft iron (pure iron, or steel that has not been hardened), we find we are very successful as long as the current runs in the magnetizing coil. When the current is switched off, the bar loses nearly all its magnetization. Soft iron makes an excellent temporary magnet, and it is therefore used for the cores of electromagnets in motors, etc.

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*Taken from Eric M. Rogers, *Physics for the Inquiring Mind*, Princeton University Press, Princeton, N.J., 1960, p. 573.

INVESTIGATION 24: ELECTRICITY AND MAGNETISM

We can magnetize a soft iron bar temporarily by bringing a magnet near it. If the N-pole of a magnet is placed near the end a of a soft iron bar AB, a compass needle shows that AB becomes a magnet, with a S-pole at A, near the magnet's N-pole. It develops a N-pole at the remote end B. When we remove the magnet from AB, these poles disappear. Now you can see why unmagnetized iron filings are attracted to a magnet. In the magnet's field, near the magnet, these small chips of iron are magnetized temporarily, and their poles experience unequal pulls and pushes. A chip of iron near a magnet's N-pole will develop a temporary S-pole near the magnet's N-pole, and this S-pole will be attracted strongly by the magnet's N-pole. The chip also has a N-pule, but this is farther from the magnet, therefore in a weaker field. So the chip is more strongly attracted then repelled, and is pulled towards the magnet.

On a larger scale, a magnet attracts any unmagnetized piece of iron, by producing temporary magnetization. Even a small compass needle will magnetize an iron bar temporarily. Being more easily movable than the large bar, the needle will turn and point to it. Such turning merely tells us that both needle and bar can be magnetized and that at least one is magnetized. We cannot tell from such attraction whether both are magnets. We can tell, however, if we find repulsion.

* Taken from Eric M. Rogers, Physics for the Inquiring Mind, Princeton University Press, Princeton, N.J., 1960, p. 573.

READING: ELECTRICAL METERS

You have used electrical meters in many of the investigations you have done. You used them as a black box—that is, the meter was a gadget that did what you wanted it to do but you made no attempt to understand it. Black box simply means how something works is hidden from your view.

All electrical meters depend upon three basic properties of electricity and magnetism.

INVESTIGATION 24: ELECTRICITY AND MAGNETISM

1. Electric currents have accompanying magnetic fields and that magnetic field surrounds the current-carrying conductor. In Investigation 24, you found how to use your hand and fingers to find the direction of the magnetic field of the current.

2. A magnetic field has a direction. It also has a strength or magnitude. Since a magnetic field has a magnitude and a direction, it is a vector.

3. The vectors representing two magnetic fields can be added just like any vectors. (You may wish to review Investigation 2.)

Suppose you had one magnetic field whose directions was completely vertical and straight up? You also have a magnetic field whose direction is completely horizontal and to the right (see Figure 1). The magnitudes of the two fields are exactly the same. You knew what the direction of the resultant magnetic field would be. It would be in between the vectors of the two fields. Any object that is susceptible to magnetism would experience a force in the direction of the resultant field. Furthermore, if that object is movable, it will move in the direction of the resultant field.

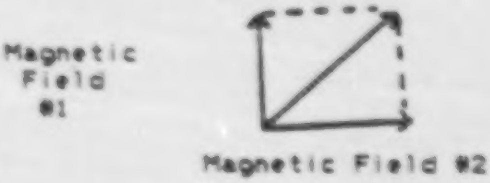

Figure 1

Suppose I had a magnetic field like the one shown in Figure 2. The pole faces are curved to direct the magnetic field. The soft iron between the poles concentrates the field. The direction of the magnetic field is from N to S.

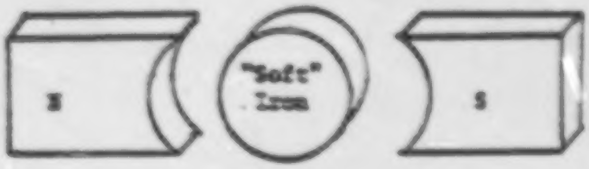

Figure 2

INVESTIGATION 24: ELECTRICITY AND MAGNETISM

A non-magnetic frame--such as a plastic--is now wrapped with many turns of wire (see Figure 3). The frame is pivoted to enable it to turn about its exact geometrical center. An electrical current is now sent through the wire in the direction indicated. If you use the hand rules you learned in Investigation 24, you will find the direction of the magnet field is toward the top of the page.

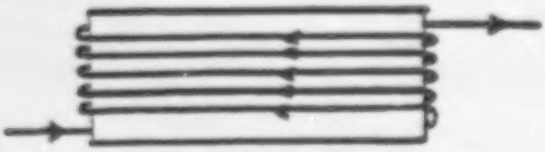

Figure 3

The non-magnetic frame is now fastened to the soft iron in the middle of the magnetic field of Figure 1. The frame and its windings of wire are fastened at the middle so they are free to rotate about the pivot point. Current is now sent through the windings on the frame. The vector diagram in Figure 2 shows you the direction in which the coil and frame will move.

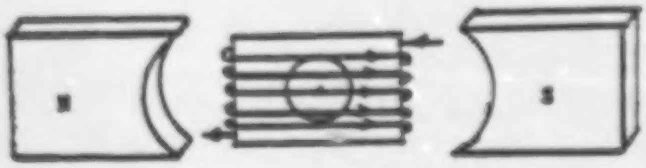

Figure 4

The diagram in Figure 4 shows the basic working parts of a galvanometer. It was named for Luigi Galvani (1737-1798), an Italian scientist who did the basic work in developing electrical energy cells. A pointer and a scale are attached to the apparatus to make it more convenient to use (see Figure 5). Regardless of what is added to a galvanometer, however, it operates because of the interaction of two magnetic fields.

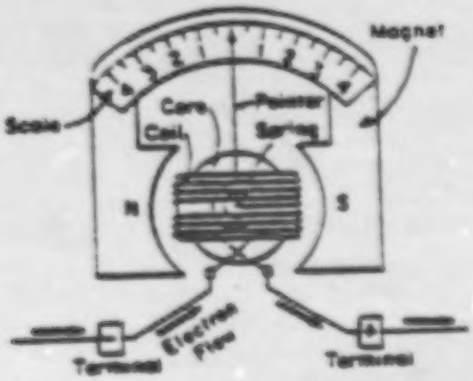

Figure 5

A galvanometer is a very sensitive instrument. All currents, regardless how small, have a magnetic field. So the needle moves with the smallest possible current. You have measured quite large currents with the instruments you have used. Those currents would have caused such a large magnetic field that the needle would have slammed against one side or the other of the scale. The galvanometer is not too useful to measure large current flowing in a circuit.

To overcome the deficiency of the galvanometer, special adjustments need to be made upon it. The wire which carries the current establishing the magnetic field is made of a high resistance.

Now if a lot of current were pushed through that resistance, the coil would burn up. But suppose a lower resistance wire were hooked in parallel with the current carrying coil. Most of the current would pass through the lower resistance coil. In other words, most of the current would be shunted away from the main galvanometer coil. That low resistance wire is called a shunt (see Figure 6). The voltage drop between the terminals, however, would be the same in the galvanometer coil and the shunt. The scale reading can be adjusted, therefore, to accurately reflect that portion of the current in the shunt and that portion in the galvanometer coil.

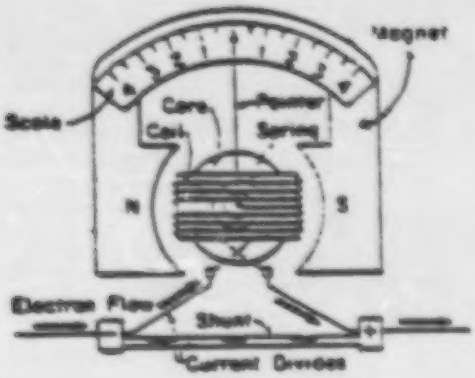

Figure 6

A galvanometer that has had a shunt added to it measures electrical current. It is called an ammeter. Not infrequently, ammeters have several scales, each one reading a higher amount of current. Each scale has its own shunt. The resistance of the shunt has been carefully worked out to enable the readings on the scales to be accurate.

The resistance of the galvanometer coil controls the current flowing in that coil when an electrical energy source is placed across the terminals of the galvanometer. The current flowing through that coil (according to Ohm's Law) will lose (or drop) voltage as it flows through the coil. The current drops voltage because the coil has resistance. Suppose a needle and scale were attached to the galvanometer. That amount of voltage loss would cause the needle to deflect as far as the scale would allow it to go. In other words that amount of voltage loss causes a full-scale deflection. The galvanometer is now being used as a voltage meter or voltmeter.

But suppose you wanted to measure more voltage than that causing a full-scale deflection. The current needs to get rid of, or drop, voltage on a resistor other than the galvanometer coil. You studied electrical circuits in Investigation 21. You know that if resistors are hooked in series, the sum of the voltage drops across all the resistors equals the voltage of the source across all of them.

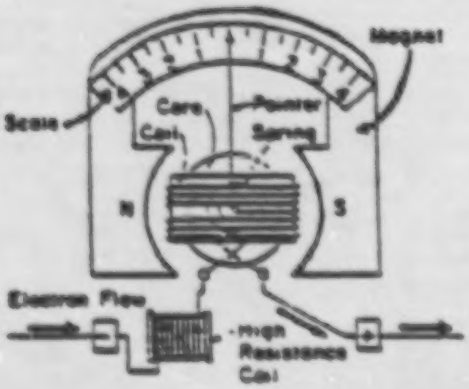
Magnet
Scale
Core
Coil
Pointer
Spring
N
S
Electron Flow
High Resistance Coil

Figure 7

Study Figure 7. A high resistance coil has been placed in series with the galvanometer coil the voltage dropped across the - and + terminals would equal the voltage of the source placed across them. That means the galvanometer and coil will now allow higher voltages to be read on its scale than could be read with just a galvanometer. The resistance hooked in series with the galvanometer has multiplied the scale of the galvanometer.

That coil hooked in series is called a multiplier. The value of the resistance of a multiplier resistor will allow the needle to deflect full-scale. Now if the scale is to be multiplied by several different factors, different multiplier resistors must be used. Each of them is hooked in series with the galvanometer coil as shown in Figure 8.

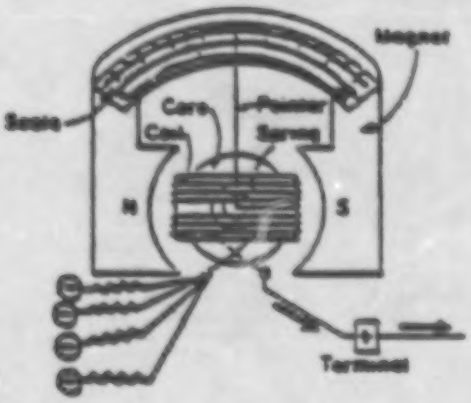
Magnet
Scale
Core
Coil
Pointer
Spring
N
S
Terminal

Figure 8

The negative terminal used depends upon which scale is to be used.

INVESTIGATION 25: LIGHT STUDENT GUIDE

Name________________________

Section______________________

Introduction

In the next several investigations, you will be studying light. Some of your time will be spent studying what light is and part of the time you will investigate how light acts under certain conditions.

The subject of light has intrigued physicists for centuries and advancements in understanding its nature have been made expecially in the last 300 years. Even with all the investigation that has been done, the exact nature of light is still not known to the satisfaction of physicists.

Exploration

1. You will be given a light source; you will also be given a device called a radiometer. Shine light on the vanes of the radiometer. Describe what happens inside the radiometer when light shines on it.

   ____

   ____

2. Turn off the light. If you see no change in the behavior of the radiometer's vanes, you may have to turn off your room lights. What happens inside the radiometer when you do that?

   ____

   ____

3. What effect does light have on the radiometer vanes?

   ____

   ____

The Idea

4. Recall from your previous investigations that when a force is evidenced by the acceleration of a mass through a certain distance, work has been done. What evidence do you have that light is doing work on the vanes of the radiometer?

5. What can you say about light as a result of your experience with the radiometer?

Name____________________

Section____________________

Expansion of the Idea

Part 1: Questions on the Heat-Light Relationship

1. Explain why, after your car has been sitting in the sunlight, the temperature inside is greater than outside.

2. Explain why a lighted 100 watt light bulb is brighter than a 60 watt light bulb.

3. Consider the following facts:

Land heats up faster during the day than water
Warmer air rises, cooler air falls
Land cools off faster at night than water
Wind is air moving across the surface of the earth.

Use the above statements to explain the following:

a. Why does wind blow from sea to land on a clear hot day?

b. Why does wind blow from land to sea at night?

c. How is wind a result of light energy changed to heat?

Name____________________

Section___________________

Expansion of the Idea

Part 2: Questions on the Readings

1. List the forms of solar energy discussed in the reading, Solar Energy.

2. What is involved in making each form of energy useful to us?

3. Notice that the units of solar energy used are kilowatts/meter2 which is power/area. Think about and explain why this unit is useful for talking about solar energy.

4. What is the photoelectric effect?

5. What problems make solar energy technology difficult?

6. What possible solutions to the solar-energy technology problems are being explored?

7. Explain the statement, "We know that 100% efficiency is not possible."

8. React to the statement in Question 7 expressing reasons for your agreement or disagreement. (Review Investigation 18, if you need help.)

READING: SOLAR ENERGY

Every second, the sun changes 596 million metric tons of hydrogen into 592 metric tons of helium, by a process known as nuclear fusion. The 4 million metric tons that are missing are spewed out of the sun as energy, which we see a part of as light. This energy is equivalent to the energy released by burning 93×10^{17} liters of gasoline. That's a 93 with 17 zeros following it, which is a number too large to imagine. But all is not lost. The earth, because it is so far away, receives only one two-billionth of this energy. So, the energy received from the sun by the earth every second is equivalent to what would be released by burning only 1.86×10^{8} liters of gasoline. That's enough gasoline to let you and over 4 million friends, each driving alone, drive once around the earth's equator. You would certainly wear out a lot of tires.

To look at it another way, the rate at which energy from the sun strikes the earth would mean that it would take four hours to fill the bodies of water which are called together San Francisco Bay with the equivalent amount of gasoline.

Keep in mind that this much energy from the sun comes to the earth every second. However, not all of this energy reaches the earth's surface. About half of it reflects from the atmosphere without reaching the ground. Nonetheless, even a small fraction of this is more energy than mankind could ever reasonably expect to use.

All of this energy is raining down all over, free of charge. It's there just waiting to be used. And that's the catch. There are so many ways to put the sun's gift to use that it is mind-boggling, but very few of them have been well developed. Even fewer have been put to what could even generously be called wide-spread use.

The most obvious form of solar energy is direct sunlight. Sunlight can be used to generate electricity directly, through photovoltaics, which will be discussed in another reading, or the warmth of the sun can be used directly for heat. At least 20% of the energy used in the U.S. goes for heating uses. Solar collectors are becoming increasingly more common, and are quite simple in idea, even though any particular design may be very complicated. Every solar heating system has a method of collecting the heat, a method of storing it, and some way to move heat from collector to storage.

INVESTIGATION 25: LIGHT

Solar furnaces also use solar heat directly. Usually, mirrors reflect sunlight and concentrate it at one point, creating very high temperatures. In France, there is a solar furnace with heliostat (sun-tracking) mirrors that can reach a temperature of over 3300°C in less than one minute. Smaller solar furnaces have been proposed as heat sources to boil water for steam turbine generation of electricity.

Many forms of energy are solar energy, even though they may not seem like it. When the sun shines down it heats the air, which rises. To fill the gap left by the warmer air, which is ascending skyward, cooler air rushes in, making wind. Farmers have used windmills for a long time to pump water, and until the most recent years, wind chargers for batteries were fairly common on farms, because power lines hadn't reached many farms. Making more efficient use of the wind, and exploring the use of windmills for large scale power generation are current research topics. For example, a study done at Oklahoma State University showed that 0.2 Kw/m^2 of area perpendicular to the wind direction is the average availability of wind energy in the Oklahoma City Area. This is roughly the same amount of energy that would be available from direct solar energy, if you average the solar energy over 24 hours per day for all seasons and weather conditions. Wind power can, at this time, be recovered more efficiently (40%) than the best direct solar generation available (16%).

Sunlight also evaporates water, which returns to earth as rain, sleet, snow, or hail. This water can be stored in reservoirs, and run through turbines for hydro-electric (water-powered) generation of electricity. Approximately 80% of the potential energy stored in water can be recovered by a hydro-electric generator.

Sunshine is also used to grow crops, which can provide energy three ways, only two of which are commercially feasible. First, they can be eaten, which is satisfying, but won't run your television. Beyond this, they can be dried and used as burning fuel for boilers, or they can be fermented to produce methane. Methane is very similar to what we call natural gas, and can be stored, distributed, and used in the same way.

INVESTIGATION 25: LIGHT

The upper layers of the seas and oceans are warmer than the lower, deeper layers, due to the sun's rays upon them. There have been proposals to put this thermal gradient (temperature difference) to use for generation of electricity. A substance that would be a gas at warm surface temperatures and a liquid in the colder depths (such as propane or ammonia) could be used in a closed cycle. It would evaporate and force through generating turbines near or at the surface, and cycle through closed pipes in deeper water to condense to a liquid again.

None of these proposals have been fully developed, and each has its own advantages and draw-backs. Some of these ideas might only be feasible for a small proportion of the population, or for small areas of the world. But every kilowatt-hour of energy that is generated from a direct or indirect solar energy is a kilowatt-hour that won't have to be generated from expendable fuels or polluting sources--in effect, we have saved that kilowatt-hour. So, to paraphrase Ben Franklin, 'a joule saved is a joule earned.'

READING: THE PHOTOELECTRIC EFFECT

Perhaps you have come to an entrance to a commercial building and for no obvious cause the door opened in front of you. You did not push it open; no one pulled it open. You did not push a button nor step on a pressure sensitive mat, but suddenly the door opened. The door may have opened electrically, triggered by a photoelectric cell. When your body broke the beam of light, the cell triggered the electric motor and the door opened.

Photoelectric cells are coming into increasingly wider use every year. Your camera may have one to set the shutter opening size. You, then, tell you friends that you have a camera with an automatic shuttter. There are photoelectrically controlled burglar alarms. The sound track of movie projectors operates photoelectrically. Also, a solar-powered watch has been invented and marketed. The watch is powered by a photo-cell.

INVESTIGATION 25: LIGHT

The idea behind the photoelectric effect was first presented in 1905 by Albert Einstein. Dr. Einstein was attempting to explain something that had first been noticed in the laboratory of Heinrich Hertz in 1887 or 1888. Hertz had been studying the spark that jumped between two small metal spheres that were placed close together and charged oppositely by an induction coil. What Hertz found was that the spark jumped more readily when he polished the two metal spheres. Further investigation showed that the polishing had the effect of allowing light to interact with the clean metal surface and under these conditions the metal gave off some electrical charge. The charge was not great enough to be observed by itself, but its enhancing of the spark produced by the coil was observable. It was this effect called the photoelectric effect which Dr. Einstein explained in 1905 and for which he received the Nobel Prize for physics in 1921.

Although Dr. Einstein received the Nobel Prize for his work with the photoelectric effect, it is not this work for which he is the most famous. He is known for his work with relativity out of which came the famous equation $E=mc^2$.

The point of interest to us from Dr. Hertz's investigation and Dr. Einstein's work is that light can be changed to electricity under certain conditions.

It was the fact that light can be changed to electricity that has interested scientists and politicians. There has been and continues to be research for ways of increasing the electricity yield of photoelectric materials so that they can be marketed as energy sources. So far, even when such materials are placed in direct sunlight, the electric current so produced could only be described as a trickle.

The basic ideas of using solar energy are rather simple—conversion of light to other forms of energy, especially electricity—but the technology (the designing and building of devices to do that) is another story. There is a number of problems which make the design work difficult.

First of all, the sun's energy is available at any one place only half the time. At night and on cloudy days energy from the sun is either not available or diminished. That means we must develop the capability of storing energy when it is available from the sun so that we can use it when the sun's energy is not accessible.

Another problem is that the sun's energy is spread out all over the earth. That means the energy is not concentrated at any one place so small energy converters will not individually convert much light into electricity. Solar power is available at about 1353 watts of power, about enough to run a hand-held hair blower. We know that 100% efficiency is not possible. Part of the scientists' and engineers' task is to design solar converters which will make the conversion process as efficient as possible.

At the present time, solar technology is still more expensive to set up than other forms of energy conversion. Solar devices will have to become less costly before many people will buy them and put them to use. No matter how good a solar device is, it will not replace other energy sources and save energy if nobody uses it.

None of these problems are unsolvable, but the search for the best solutions may take some time. Several possibilities are already being explored.

Energy storage appears to be a better choice than long-range power transmission. There are many good ideas for energy storage just waiting to be developed. It would take far too many batteries, the way they are built today, to store enough energy to last through nights and cloudy days. So research is going on now to develop more efficient batteries. Another possibility is to use solar-generated electricity to electrolyze water (electrically break it down into hydrogen and oxygen), storing the hydrogen and oxygen to serve as fuel to power boilers in steam generators when the sun isn't shining. Or, water (whole molecules) could be given potential energy by pumping it uphill when the sun is out, and letting it fall through hydro-electric generators to generate electricity when the sun's energy is not available.

INVESTIGATION 25: LIGHT

One product which appears to promise greater amounts of electricity in the future is the photovoltaic cell. The light converting material in such cells is generally the element silicon, which is produced in wafer shapes for photovoltaic cells. When light strikes the silicon wafer, electricity is produced. The production amounts per wafer are still very low, but putting many wafers side by side can increase the amount of electricity produced. Some buildings are now being partially powered by solar energy through the use of these photovoltaic cells which are mounted on the roofs. There is evidence to indicate that photovoltaic cells will become cheaper and more efficient in the future as their technology improves.

The potential uses for photovoltaic power systems are enormous. One of the greatest advantages of them is that their initial cost is the major expenditure--maintenance will cost little--whereas the cost of fuel for diesel and gasoline generators will continue to rise. They can be combined with storage batteries to provide lighting for streets, construction sites, parking lots, airport runways, bridges and buildings (night lighting). The combination of storage systems and photovoltaic power systems could be used to operate power tools in machine shops and pumps to pump water and fuel on farms. One of the advantages of this arrangement is that the power unit and battery are self-contained. One does not have to connect to city power lines and pay for the energy.

The power cells convert light to electricity during the day or while they are not in use. Then at night or while they are in used, the energy stored in the battery can be used.

The potential uses of photovoltaics indicate that the nation is only scratching the surface in its use of solar power as a source of energy. Once photovoltaics and other continuously produced sources of solar energy (such as wind, crop fuel, and others) are made economically feasible for marketing, the need for engineers to design saleable systems will greatly increase.

Name______________________________.

Section____________________________

Introduction

In the previous investigation, you learned about some of the properties of light. Light is a form of energy and is capable of doing work. This investigation is the first of a series in which we will investigate ways light interacts with objects having various properties. The first investigation into the behavior of light deals with its interactions with plane mirrors.

Exploration

Attach a sheet of unlined paper to a piece of cardboard. Use a ruler and draw a straight line across the middle of the paper and label that line MN. Get a rectangular wooden block and, using a rubber band or adhesive on the back of the mirror, attach the mirror to the block. Set the mirror on line MN at a right angle to the paper.

Most mirrors have a reflective substance (mercury or silver in more expensive mirrors; aluminum in cheaper mirrors) sealed to the back of a very clean, smooth piece of glass and covered with a protective coating. Light rays that reflect (bounce off) from the mirror actually do so from the back of the mirror.

Place two pins straight-up in the sheet so that a line between the two pins could be extended toward the middle of the mirror and would make an angle less than 90° with the mirror.

Extend the line between the pins until it intersects with line MN. Your paper should look somewhat like the drawing shown in Figure 1.

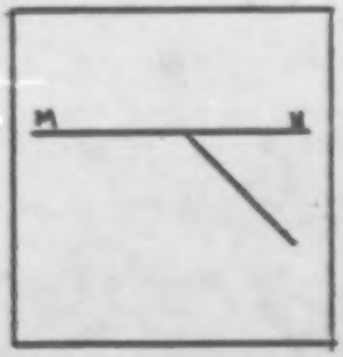

Figure 1

With your eye level slightly above the paper, look between the M end of line MN and where the line you have drawn connecting the two pins touches the mirror (see Figure 1). You should see the reflections of the two pins. Move around until those reflections are in a straight line. Place two more pins between your eyes and the mirror in a straight line with the reflections in the mirror; the reflections and the pins should be all in one straight line.

Remove all four pins and draw a line which connects the pin holes of the first two and intersects the mirror. Draw a second line that connects the second two pins and intersects the mirror. The two lines you just drew should intersect the mirror at the same point.

You have just made an assumption about how light travels. You assumed that the light from the pins traveled in a straight line from the pins into the mirror. You drew a straight line which told you the direction the light traveled to the mirror. You also assumed that light traveled in a straight lline out from the mirror and that light allows you to see the reflections of the pins. You have assumed that light travels in straight lines and those straight lines are called light rays. Do light rays actually exist? Whether or not light rays actually exist is not important, because the laws of light which you will develop in your studies act as though they do. A light ray is a model. Now to interpreting the data just collected.

Draw a line perpendicular to line MN and joining MN at the point the two lines you drew intersect the mirror. That perpendicular line is called the normal.

1. Measure the angle between the incoming light ray from the pins and the normal (the incoming light ray is the incident ray). Record the value of that angle here.

   ____

   That angle is known as the angle of incidence.

2. Measure the angle between the normal and light ray coming out from the mirror that comes from the reflection of the pins (the light ray coming out is called the reflected ray). Record the value of that angle here.

   ____

   That angle is known as the angle of reflection.

3. Now, repeat the experiment you just did using a different angle of incidence. Record the data from both experiments in the table below.

Table I

Experiment	Angle of Incidence	Angle of Reflection
1		
2		

4. Get data on the measured angle of incidence and reflection from two other groups of students. Record those data in the table shown below.

Table II

	Experiment	Angle of Incidence	Angle of Reflection
Group 1	1		
	2		
Group 2	1		
	2		

The Idea

5. You now have six values for each of the angles of incidence and reflection. What do you interpret from those data? Make a statement of interpretation here.

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Name__________________________

Section________________________

Expansion of the Idea

Part 1: Problems

Two mirrors are set up as shown in Figure 2. Those mirrors have a 90° angle between them. Light rays may enter from any direction. (Do not consider rays which will hit the junction between the mirrors or rays which do not reflect from one mirror onto the other one.)

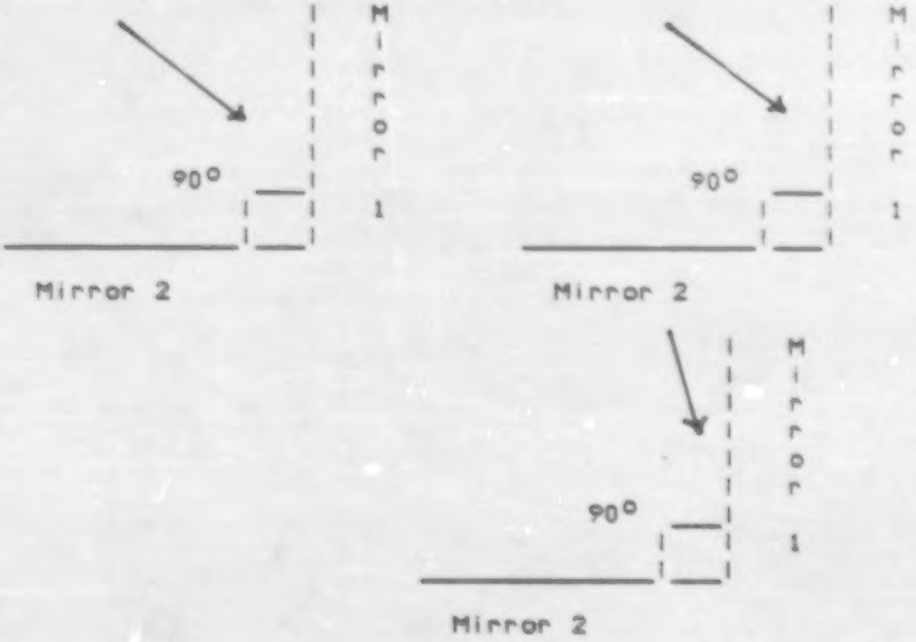

Figure 2

1. Consider several rays entering the mirror system. Determine the direction of the reflected rays after they have reflected from both mirrors. State a general rule which describes how the direction of the reflected ray is related to the direction of the incident ray for mirror at 90°.

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2. A man who is six feet tall (from his eyes to the floor) is looking straight ahead at himself in a mirror that is eight feet away from him. The mirror is perpendicular to the floor.

   a. What is the shortest mirror in which he will be able to see himself from eye to toe? Why did you choose this length? (Hint: Draw a diagram and use light rays.)

   b. How would your answer to Question a. change if the distance between the man and the mirror were doubled?

Name________________________

Section________________________

Expansion of the Idea

Part 2: Reading Questions

1. According to the reading, A Plane, but Not Dull, Story, how is the law of reflection applied to determine strain patterns in airplane wings?

2. From the reading, Front-Surface Mirrors, how are most common mirrors made?

3. What advantages are realized from front-surface mirrors?

4. Give one example, from the reading, of the use of a front-surface mirror.

INVESTIGATION 26: LIGHT AND PLANE MIRRORS

READING: FRONT-SURFACE MIRRORS

If you look around you, at school and at home, the chances are very good that every mirror you see will have its reflecting surface sealed to the back of a plate of glass. When you want to see a reflection, you must look through the glass to see the reflecting surface.

For most home, business, and industrial uses, the small amount of distortion introduced by the glass (which will be studied more thoroughly in another investigation) is unimportant, and glass-fronted mirrors have an advantage: since the reflecting surface of this type mirror is the interface between the glass and the reflecting surface, the surface is protected. It will not get dirty or scratched (although the glass will), and you can put a very sturdy protective covering over the reflecting surface without impeding its reflective properties.

In many scientific applications, however, the glass layer becomes an important factor. For example, astronomical instruments must be capable of measuring extremely small differences in angles (down to 2 seconds of arc, or 2/3600 of a degree), and adding a layer of glass on top of the reflector makes that precision even more difficult to attain.

As a result of this need for precision, sciences such as interferometry and astronomy have encouraged the advancement of development of front-surface mirrors. Front-surface mirrors have a layer of metallic reflector (silver is more reflective, but aluminum is more durable and much more commonly used) attached to the front of a very smooth surface, usually glass, because it is easily polished.

The best-known example of a front-surface mirror in the United States is the 508 cm reflecting mirror of the Hale telescope at the Mt. Palomar Observatory in California. The disk for the mirror was cast in 1934 of Pyrex glass, with the back ribbed for strength and stiffness. After the glass disk cooled, eleven years were spent grinding and polishing the front surface to a high degree of precision. During the grinding and polishing process, over five tons of glass were ground off! After the disk was ground to precision, a thin layer of aluminum was applied to its front surface, and the fifteen ton mirror was installed in the telescope at the Mt. Palomar Observatory in 1948.

INVESTIGATION 26: LIGHT AND PLANE MIRRORS

This huge telescope, weighing over 500 tons altogether and controlled by computer, is capable of gathering 800,000 times as much light as the human eye, and has mapped the entire sky, taking photographs of objects that are several billion light-years away. The National Geographic Society-Palomar Observatory Sky Atlas compiled by this front-surface telescope is a standard reference work in astronomy.

READING: A PLANE, BUT NOT DULL STORY

Once upon a time, an engineer was designing an airplane. He wanted the airplane to be able to do tricks, like diving very steeply toward the ground, and pulling out at the last minute. But that type of trick puts great amounts of strain on the wings of an airplane, because it takes very large amounts of force to give an airplane the amount of acceleration it needs to change direction that suddenly. Our hero needed to be able to tell where the most strain was being put on the wings, so that he could reinforce those places, or redesign the airplane.

One way to find the points of maximum strain on an airplane's wings is to keep straining them until they break, usually in flight. Then you go around picking up the pieces of the airplane and try to figure out which damage to the plane caused the crash and which damage was caused by it. Another method might be to follow the plane in another plane, taking movies, until the plane you are studying strains itself too much and crashes. After this, you go back and look at the film to see which part of the plane broke first.

Both of these methods will let you find points of too much strain in airplanes, but they have some drawbacks. A lot of pilots would not consider these to be very friendly methods of testing aircraft design; you would be forever picking up pieces of broken airplanes, and it could get to be rather expensive.

Our engineer friend found a better way. Since light reflects so readily from shiny metallic surfaces, and most airplanes are shiny and metallic, there should be some way to use the reflection of light to help solve the problem. And there is.

INVESTIGATION 26: LIGHT AND PLANE MIRRORS

If you shine a light on the wing of an airplane, the reflections will give a certain appearance. If you do not move, and since you know that angle i=angle r when light reflects, if a reflection changes in appearance, then one of two things must have happened. Either the light source has moved, or something about the reflecting surface has been altered.

So our protagonist sets up the following testing situation. The observer (a camera, usually) is in a stationary position, as is the light source. A model of the proposed airplane design is placed in a device that can place certain amounts of strain on objects (such as airplane models), and the light source is turned on. As the rays from the light source strike the surface, they obediently follow the law of reflection (incident angle=reflected angle), yielding reflection patterns which are predictable given the shape of the wing. Once the nonstressed reflection patterns for the wings have been recorded, the strain machine is turned on.

As the airplane model is strained to various degrees, pictures are taken and later analyzed. Changes in reflection will show up in these pictures showing places where the airplane's wings (reflecting surfaces) have changed shape under stress, causing the reflection pattern to change. These changes indicate possible trouble spots for designers to check. Airplanes are designed to flex under strain somewhat, but too much flexing, or flexibility in the wrong places, can lead to unpleasant surprises such as wings that fall off.

A knowledge of reflection can help the engineer to avoid these problems, and to build safer airplanes, which may let him stay friendly with pilots, and gives you something to think about.

INVESTIGATION 27: LIGHT AND CONCAVE MIRRORS STUDENT GUIDE

Name________________________

Section______________________

Introduction

You have just used a plane mirror and found the Law of Reflection! That law states that the angle of incidence is equal to the angle of reflection. Be sure you understand how to measure the angles of incidence and reflection and what the normal line means.

A curved mirror and three entering light rays are shown below. Using the Law of Reflection, draw rays to show what would happen to the three entering light rays after they leave the mirror shown in Figure 1.

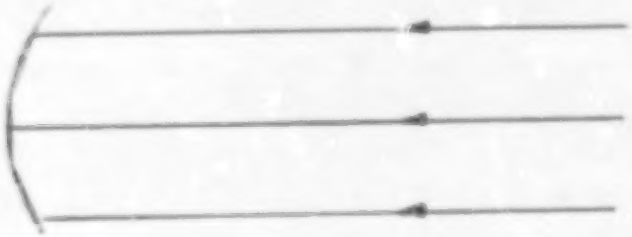

Figure 1

In this investigation, you will be using curved mirrors similar to the one shown above. Such a mirror is known as concave. This class of mirrors also includes spherical mirrors because such a mirror could be part of a sphere.

For this investigation, you will be using concave mirrors to study the reflection of light. The Law of Reflection is useful in this investigation; so do not forget the requirements for its use.

Exploration

1. You will need a concave mirror, a white card and a meterstick. Stand by a window so the reflections of objects outside can be seen in the mirror. You may wish to go outside to do this experiment. If you do, stand in the shade and study reflections from objects in the light. Describe the images you see in the mirror.

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2. Hold the mirror very still and have your partner move the card around until you see an image on the card. Be sure the object whose image is on the card is quite far away. Describe the image seen on the card.

____

____

3. Measure the distance form the mirror to the card. Call that distance the image distance, d_i. Record that measured distance in Table I in the d_i column. Measure or estimate the distance from the mirror to the object whose image is on the card. (Measure the length of a step and then count the steps between the mirror and the object. If the distance is more than ten meters, do not bother to measure it. Just record more than 10 meters.) Call that distance the object distance, d_o. Record the value of d_o in Table I.

Table I

	d_o(m)	d_i(cm)
1		
2		
3		
4		
5		
6		

4. On the axis below, plot a graph of d_o versus d_i. What does the graph allow you to say about d_i when d_o is large (when compared to d_i)?

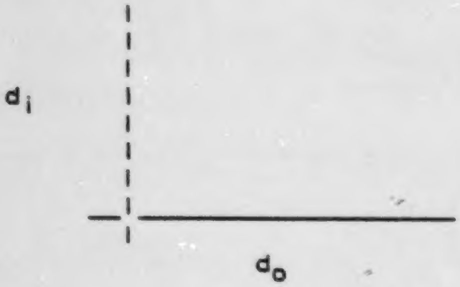

Figure 2

The Idea

1. Describe how the six values of d_i compare.

2. Describe how the six values of d_o compare.

3. Write a statement which compares d_o and d_i.

4. The statement in Question 3 is a description of the focal length (f) of a concave mirror. What is the special condition that must be present before $d_i = f$?

5. Explain how the graph of the data in Table I supports the focal length idea?

INVESTIGATION 27: LIGHT AND CONCAVE MIRRORS STUDENT GUIDE

Name________________________

Section_____________________

Expansion of the Idea

Part 1: A Model

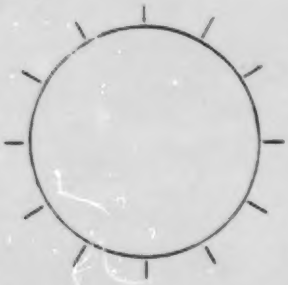

Figure 3

The sun is approximately $93\text{x}10^6$ miles from the earth. This distance certainly qualifies as a large distance and if you focused the sun on a piece of paper, the distance from the lens would represent the focal length of the lens.

CAUTION: DO NOT focus the sun's rays on Paper. You could start a fire and if you look at the focused sun, you could permanently damage your eyes.

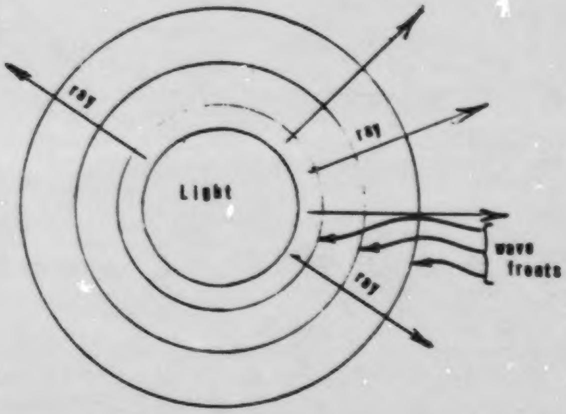

Figure 4

There is a special way to look at how light travels and that way involves something called wave fronts. The model often used to think about how light travels says that light moves out from the source in concentric circles. You have probably seen something similar in water waves moving out from a stone being thrown in water.

A light ray is drawn _perpendicular_ to a wave front at any given point. As the wave front moves further and further away from the light source, its circle gets bigger and bigger and any section of it comes close to a straight line. Now, lines drawn _perpendicular_ to a straight line are parallel to each other. So, rays of light coming from a light source which is far away (or at a great distance) are _parallel_ to each other.

From your data, you found that the focal length of a concave mirror is the image distance when the object (the light source) is far away. In other words, the light rays from the _far away_ light source (the object you focused on the card) struck the concave mirror you used, traveling _parallel_ to each other. Keep in mind that light rays coming from distant objects travel parallel. The focal length of a concave mirror could be written as--the image distance when parallel light rays strike the concave mirror.

Name________________________

Section_____________________

Expansion of the Idea

Part 2: An Experiment

Set up your equipment by placing the mirror and screen in their holders and placing them on the meter sticks. Arrange the two meter sticks as shown in Figure 5. Collecting these data may take longer than one class period. Be sure to use the same mirror throughout the experiment. Be sure you know the mirror's focal length.

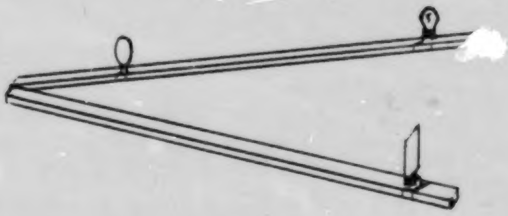

Figure 5

6. Place the mirror and the lightbulb 100 cm apart (be careful--it is even more important than usual that these data be taken carefully). Adjust the distance between the mirror and the screen until an image forms on the screen. Find the distance between the mirror and the screen which gives the sharpest image of the lightbulb on the screen. Measure this distance and record it in the image distance (d_i) column of Table II for Trial 1. Record the distance from the lightbulb to the mirror in the object distance (d_o) column. Measure the height of the light source and record it as the height of the object (h_o) for Trial 1. Describe the image.

____

____

7. Place the bulb at five other points on the meterstick where an image will be formed on the card. You may need to attach a second meterstick to the end of the area holding the mirror at the end away from the mirror. Record d_o, d_i, h_o, and h_i in Table II.

Table II

Focal length of mirror used__________________

Trial	d_o (cm)	d_i (cm)	h_o (cm)	h_i (cm)
1				
2				
3				
4				
5				
6				

8. Construct a graph of d_o versus d_i on the axis shown below.

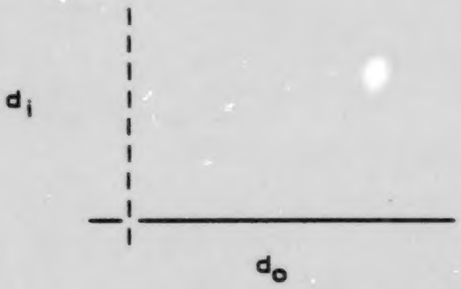

Figure 6

9. Describe how the curves in Figures 2 and 6 compare with each other.

10. What does your response to Question 9 tell you?

INVESTIGATION 27: LIGHT AND CONCAVE MIRRORS STUDENT GUIDE

Name____________________

Section____________________

Expansion of the Idea

Part 3: Ray Diagrams

A concave mirror is shown in Figure 7. As was said earlier, a concave mirror can be a spherical mirror. The sphere of which the mirror is a part has a radius, r, shown in Figure 4. That radius is known as the radius of curvature of the mirror: f0 is the focal length of the mirror.

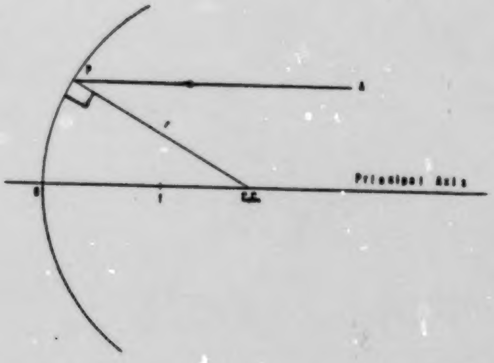

Figure 7

11. Suppose light ray A hits the mirror in Figure 7 at point A. Through what point will it be reflected? (Remember parallel light comes from a distant object.)

____

12. Draw the reflected ray into Figure 7. Label the angle between ray AP and r, 0. Label the angle between r and the reflected ray 0. What value then is the angle between the reflected ray and the principal axis?

____

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13. Explain why the angle at C.C. is 0.

____

____

14. Assume PO is a straight line. What is the tangent of 0?

____

But, O(C.C.)=r, so tan 0=PO/r. Consider triangle POf. Find its tangent. Now, use the values for the two tangents you have just written and prove that the radius of curvature, r, is twice as long as the focal length f. Or: r=2f.

Refer back to Figure 6 and your response to Question 10. You found you did not know how to handle the data given there. Your teacher probably told you that an understanding of ray diagrams would help you interpret those data and it will. Do not get discouraged and go ahead!

Ray diagrams are very useful in studying optical phenomena. The following statements, all derived from the Law of Reflection, will be useful to you in drawing ray diagrams:

a. When light strikes an object, an infinite number of reflected rays are emitted from each point on that object. If two rays from a point on the object strike a concave mirror, reflect back and then converge in front of the mirror, the point of convergence will form a point of the image which is representative of the original point on the object. Such an image is called a real image.

b. The center of curvature for a spherical mirror is equal to twice the length of the mirror's focal length.

c. The principal axis of a mirror is perpendicular to the mirror at the point that it crosses the mirror.

d. When drawing ray diagrams, at least two converging reflected rays which come from the same point on the object are needed to locate an image. You should select at least two of the following four to use in diagrams.

   1) A light ray that enters the mirror parallel to the mirror's principal axis will leave the mirror through its focal point.

   2) A light ray entering a mirror through its focal point will reflect from the mirror parallel to its major axis.

   3) A light ray that enters the mirror through the center of curvature will be reflected back on the same line.

   4) A light ray from the object which strikes the mirror at its center (vertex) will be reflected according to the Law of Reflection.

15. Why is a light ray entering the mirror through the center of curvature reflected back on the same line?

____

16. Use the information given to you in the preceding statements concerning ray diagrams and complete Figures 9 through 12. These figures have been set up to give you practice working with ray diagrams as well as to expand your ideas about the nature of images produced by the reflection of light rays from concave mirrors. You will note that the object (arrow) has been placed at various positions along the major axis. How does the placement of the object affect the nature of the image produced?

When drawing the ray diagrams, keep statement a. above firmly in mind . Here is how you may interpret that direction. Notice that rays leaving the light, leave in all directions. Notice that one goes through r, one through f, and one goes parallel to the principal axis. When drawing ray diagrams, be selective regarding which ra

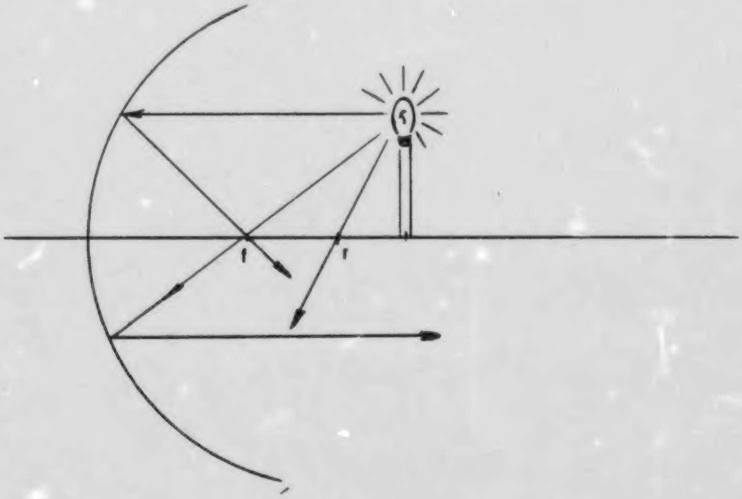


Figure 8

Now draw the ray diagrams in Figures 9 through 12.

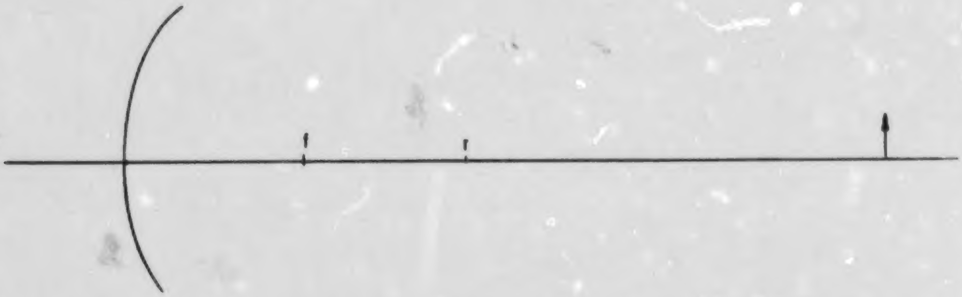


Figure 9

17. Explain why the mirror in Figure 9 produces a real image.

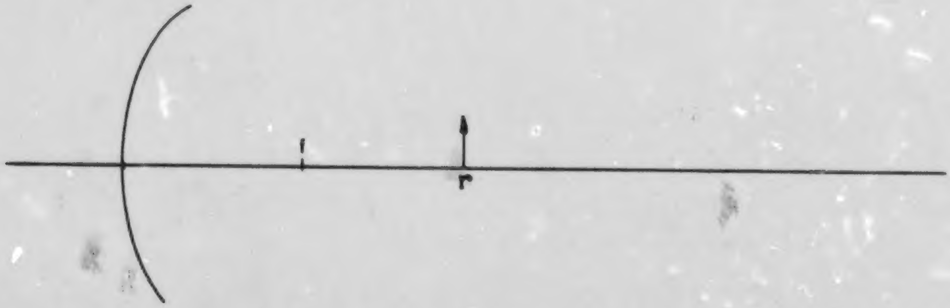


Figure 10

18. Describe the image produced in Figure 10.

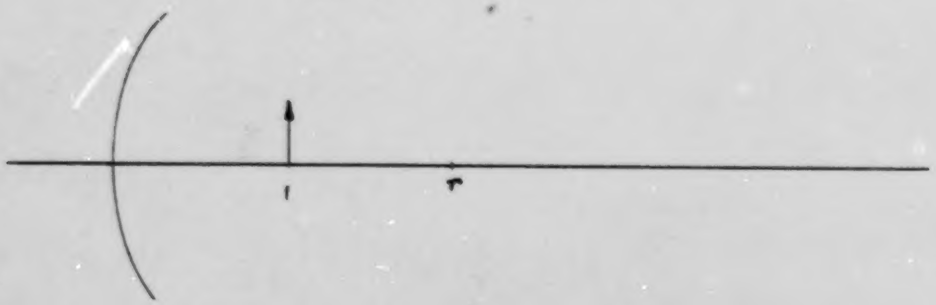


Figure 11

19. Describe the image produced in Figure 11.

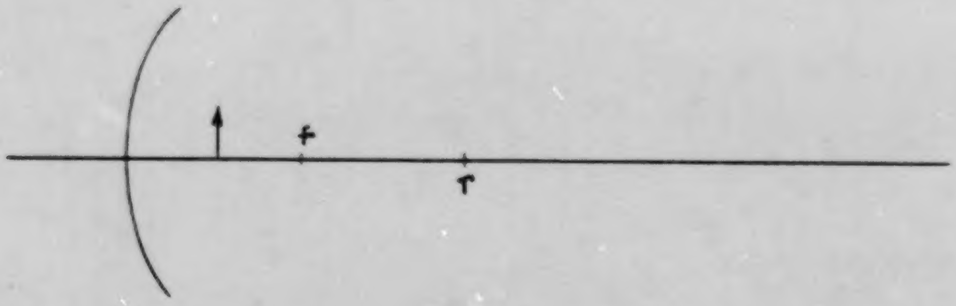


Figure 12

20. Describe the image produced in Figure 12. How does this image differ from a real image?

Name________________________

Section________________________

Expansion of the Idea

Part 4: A Verification

Use the concave mirror you used earlier. Be sure you know its exact focal length. Select two of the four ray diagrams you just drew and locate the image.

Expansion of the Idea

Part 5: A Development

You have now found out that ray diagrams produce models which are verifiable in the laboratory. That means that ray diagrams can be used to solve concave mirror problems. That turns our attention back to the data in Table II. There is, as yet, no satisfactory procedure to explain the measure you made on d_o and d_i given in that table. Such a procedure can be developed with ray diagrams.

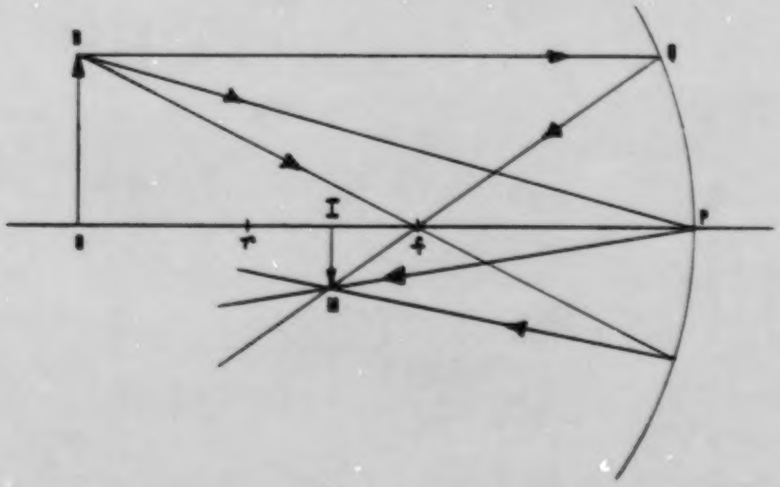


Figure 13

In developing a procedure to handle the data in Table II, on approximation must be made. That approximation is that the segment QP on the mirror approaches a straight line; that assumption then makes BQ=OP. In finding that the length of the radius of the sphere from which the spherical mirror was taken was twice the length of the mirror's focal length, you used trigonometry. In developing a tool to handle the data in Table II, you are asked to use geometry. Begin using geometry by reminding your self that:

line fP=focal length of the mirror
line OP=object distance, d_o
line IP=image distance, d_i.

21. Now, consider triangles IFM and QfP. Prove that those triangles are similar and see what that means.

22. Now consider triangles BOP and IPM. Prove that those triangles are similar and see what that means.

23. Combine the results from working with the two pair of similar triangles. That combination will produce a tool which lets you handle the data in Table II.

24. Use the tool equation you developed in Question 23 on the data in Table II. Remember you recorded the focal length of the mirror you need to collect the data. Use that value and d_o OR d_i and calculate the other. Write an evaluation of the equation you developed in Question 23.

INVESTIGATION 27: LIGHT AND CONCAVE MIRRORS   STUDENT GUIDE

Name__________________________

Section_______________________

Expansion of the Idea

Part 6: Magnification

Look at the h_o and h_i columns in Table II. Divide h_i by h_o. Calculate several of those values in the space below.

Lets play with h_o and h_i! Look at Figure 13. $h_o=BO$ and $h_i=IM$. But, $h_i/h_o=IM/BO=d_i/d_o$. So, magnification can be calculated by using the distance the object and image are from the mirror. That is, perhaps, more convenient than measuring h_i and h_o.

Name________________________

Section______________________

Expansion of the Idea

Part 7: Problems

For each of the following problems, find the location and size of the image and describe whether the image will be real or virtual (which side of the mirror it will be on), erect or inverted, and magnified, enlarged or reduced.

1. An object 9.0 cm tall is placed 12.5 cm from a concave mirror with a 10 cm focal length.

2. The radius of curvature of a spherical concave mirror of small arc is 14 cm. An object 8.0 cm tall is placed 35 cm from the mirror.

3. If the object in the previous problem is moved to a position 5.0 cm from the mirror, what type of image will be produced?

Expansion of the Idea

Part 8: Reading Questions

1. Using the knowledge gained from this reading, design a set of low beam headlights for a car that will light the immediate area in front of the car, as well as some distance ahead of the car on the right (shoulder) side of the road. (HINT: it is not necessary that both headlights be identical.)

2. Design a set of high beams to illuminate the whole road ahead and shine some light on the side of the road and overhead.

3. Design a spotlight to throw a tight beam of light on a distant object.

INVESTIGATION 27: LIGHT AND CONCAVE MIRRORS

READING: TWO PARABOLIC HEADLIGHTS IS NOT THE SAME AS FOUR BOLIC HEADLIGHTS

As you drive down a two-lane highway at night, you may notice that your low-beam headlights allow you to see quite a bit farther down the road on the right side (toward the shoulder) than on the left (toward the other lane). Have you ever wondered how your headlights steer the light? Well, even if you have not, this reading will help you build a model for that phenomenon.

Automotive headlights are constructed with parabolic reflectors. Every parabola has an axis of symmetry, and if the parabola were revolved (spun) about that axis of symmetry, you would get a paraboloid of revolution. This amounts to a dish, with the deepest part of the dish being the point where the axis of symmetry crosses the parabola itself. When you build an object of this shape, and coat it with reflective material, you have a parabolic mirror.

Parabolas have certain characteristics which are similar to the spherical mirrors you used. Light rays that enter the mirror parallel to the mirror's axis of symmetry will reflect from the mirror through the mirror's focal point. Conversely, light rays that enter the mirror through the mirror's focal point will reflect from the mirror parallel to the axis of symmetry of the mirror (Figure 1). Designers of automotive headlights make good use of this latter point.

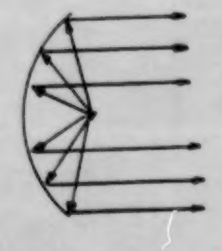


Figure 1

If the filament of a headlight is placed at the focal point of its parabolic reflector, the rays will be parallel and will illuminate an area the size of the headlight itself. This is obviously little good to you as a night driver, because this beam of light might light the license plate of a vehicle you were approaching, but would not be spread out enough to tell if it were a subcompact or semitrailer rig. The tunnel beam effect, obtained by placing the light filament at the reflector's focal point, makes it desirable to place the filament somewhere else in order to achieve the greatest effectiveness for the headlights.

As long as the filament is going to be moved, let us take time to decide what a set of headlights should do. For safest night driving, there should be two lighting choices: a low beam for lower speed driving, when there is oncoming traffic or when there is street lighting; and a high beam for higher speeds and for when there is no oncoming traffic. The low beam needs to illuminate a large area directly in front of the car, and perhaps shine down the road on the right but not on the left, so as not to blind oncoming traffic. The high beam should light the road for a substantial distance ahead, also spread some light to the side of the road, and distribute some light overhead to illuminate overhead signs and high objects.

How is it possible to do all of these things with parabolic reflectors? If the filament is deliberately offset from the reflector's focal point, the reflections will not be parallel, and a careful use of the law of reflection will predict how any displacement would alter the rays reflected from the mirror.

Placing the filament between the focal point and the reflector (behind the focal point) will cause the reflected rays to spread out (see Figure 2). Varying with how close to the focal point or how close to the mirror you place the filament, you can get changing degrees of dispersion of the light.

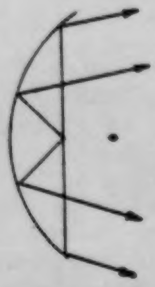


Figure 2

Placing the filament above the focal point will cause the reflected light to travel downward, and conversely, placing the filament below the focal point will reflect light upward (see Figures 3 and 4).

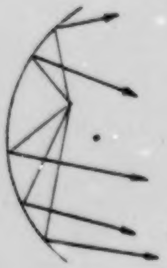


Figure 3

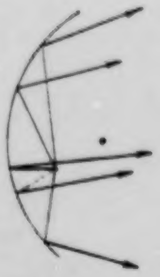


Figure 4

Also, moving the filament of the headlight to either side will throw light in the opposite direction.

Using this information, automotive engineers are able to design headlights to do very specific and specialized things.

READING: OTHER PARABOLIC REFLECTORS

It is becoming increasingly common to locate television and radio studios closer to the center of the cities and towns that they serve. This lets news reporters get from the studio to news events more easily, lets public officials come to the studio facilities with less inconvenience, and lets the station's building be visible to more of the public, which is good advertising and promotes recognition of the station. There are, however, some problems that are a part of placing studios in town.

Radio and television signals are somewhat reliant upon the local geography of an area for signal transmission. Mountains and even large hills can block a radio or Television station's signal. It is advantageous to place the signal-generating portion of the antenna as high as possible, so that line of sight transmission can be achieved for the greatest possible area. For this reason, broadcasting antennae are usually placed at the tops of tall towers, on the highest point of land that can be obtained for use in the area.

INVESTIGATION 27: LIGHT AND CONCAVE MIRRORS

Putting the studios downtown and the antenna on a hilltop can cause problems for broadcast engineers. Cities are typically built on rivers, which tend to be somewhere other than at the tops of hills, making it necessary to find the highest quality method of transmitting the signal from the studio to the antenna. Microwaves are quite well suited to this purpose, but must be carefully controlled because microwaves are potentially harmful if pointed at the wrong things.

Knowing that beams entering a reflector through the focal point will reflect parallel to the reflector's major axis has helped engineers to design microwave links from studios to antenna facilities (and even from mobile camera units to the studios). Placing the antenna from the studio at the focus of a parabolic reflector, the reflections are parallel to the reflector's major axis and can be carefully aimed at the receiving reflector (with its pickup placed at the reflector's focus) on the transmitter/antenna site.

Astronomical instruments also employ curved reflectors. Different telescope designs use many variations and combinations of reflector types, from a simple parabolic mirror in a Newtonian telescope to complex systems of hyperboloid, ellipsoid, and aspherical reflectors. The most commonly used, however, is the parabolic reflector. Radiotelescopes are almost exclusively parabolic.

Name________________________

Section_____________________

Introduction

Light naturally travels in straight lines. Throughout the investigation on mirrors, this property of light was used. Furthermore, the light was traveling in air. What happens to the path of light when it travels in a medium other than air?

Exploration

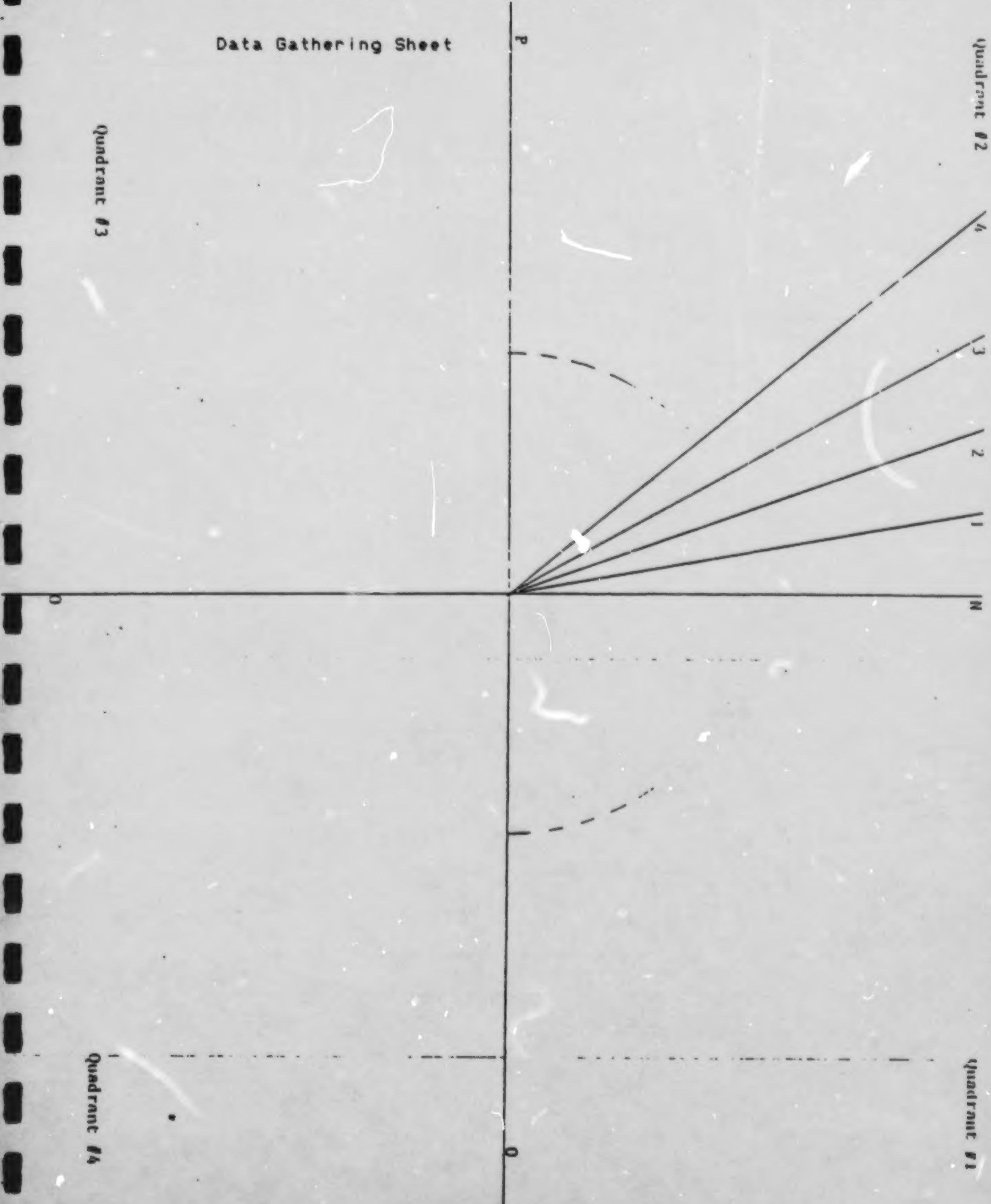
Put the piece of unlined paper on the cardboard and place the semi-circular lens on the paper. If your are using the plastic semi-circular dish, fill it with water. This disk will be called a lens (which it really is) during this investiation.

Looking through the flat side of the lens, place a straight-pin upright on the other side of the lens about 10 cm from the rounded side.

1. How is the appearance of the part of the pin that you see through air different from the part of the pin that you see through glass or water?

2. Turn the semi-circular lens slightly as if it were a wheel attached to an axle and record what happens to the appearance of the pin as the lens is rotated. Describe how much the pin appears to move (and in which direction) relative to the motion of the lens.

Data Gathering Sheet


P
Quadrant #3
Quadrant #2
4
3
2
1
0
N
Quadrant #4
Quadrant #1
0

3. Still looking through the flat side of the lens, rotate the lens in both directions until the part of the pin seen through water or glass lines up perfectly with the part of the pin seen through the air. Place a second pin (straight up) between the lens and your eye about 10 cm from the flat side of the lens. Describe the path along which the light ray from the pin probably passes through the water in order to reach your eye.

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The light from the pin which passes along a specific path can be used to describe the path of a light ray. Since the pin can be seen from any direction, there must be light rays leaving the pin in all directions. You can specify a light ray in a particular direction by placing a second pin along the path that you want to use. Then by sighting along the two pins and moving your head until the two pins appear merged, you will know that you are receiving light along a specific path.

Replace the paper on the cardboard with the Data Gathering Sheet from the Exploration section. Place the semi-circular lens in the position suggested by the semi-circular dotted line, with the flat side of the lens carefully positioned just touching the line PQ on the sheet. Notice that line NO is normal (perpendicular) to the flat side (or base) of the semi-circular lens.

4. If two pins were placed upright along the line NO between N and the lens, predict where one would have to look to see the two merged pins through the lens.

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Try it to check your prediction. Be sure to use two pins on each side of the lens.

The lines to the left of the normal represent angles at which light comes into the semi-circular lens. Measure each of the angles from the normal and record it in Table I.

5. Position two straight pins on line Number One, inserting them at different points on the line between the lens and the edge of the paper. Make them as perfectly vertical as possible and stick them through the paper into the cardboard. Using the pins, how will you find the ray of light that is coming to the semi-circular lens along the line?

6. Which direction will the light ray be travelling inside the lens?

7. Place the lens in position. Look through the lens from the base side and try to see the pins. (Be sure that you look through the lens rather than over it.) Once you find the images of the pins, move your head around until the two images merge and are lined up so that they look like one pin. Stick a pin in Quadrant Number Four near the base of the lens, at a point where you can see all three pins lined up togehter. Stick another pin in Quadrant Four and the base of the lens (on line PQ). Where does this line strike the lens?

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8. If you look at the four pins from the other direction, would they still line up? What does this tell you?

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9. Repeat Steps five through seven using lines 2, 3, and 4. Measure the angle of each of the light rays as they leave the lens (measure the angle from NO--it will be acute, or less than 90°), and record those angles in Table I on the line corresponding to the incident angles.

Table I

Line	Angle in Lens	Angle in Air
NO		
1		
2		
3		
4		

INVESTIGATION 28: REFRACTION OF LIGHT STUDENT GUIDE

The Idea

1. What happens to the angle in the air as the angle in the lens increases?

2. There is a special name for what happens to the light as it passes through the lens. It is refraction. How is refraction different from reflection?

3. There is a mathematical relationship between the angle in the lens and the angle in the air. What type of relationship does it appear to be?

4. Write the relationship between the angle in the lens and the angle in the air in the space below.

Name________________________

Section______________________

Expansion of the Idea

Part 1: A Verification

1. Use Snell's Law to help you draw the path of the light ray shown in the diagram below. Assume the block is glass, n=1.5. Draw the path in the glass and show the ray emerging from the glass. Then attach this paper to a sheet of corrugated cardboard, use a rectangular piece of glass provided by your teacher and check your drawing with the pins method.

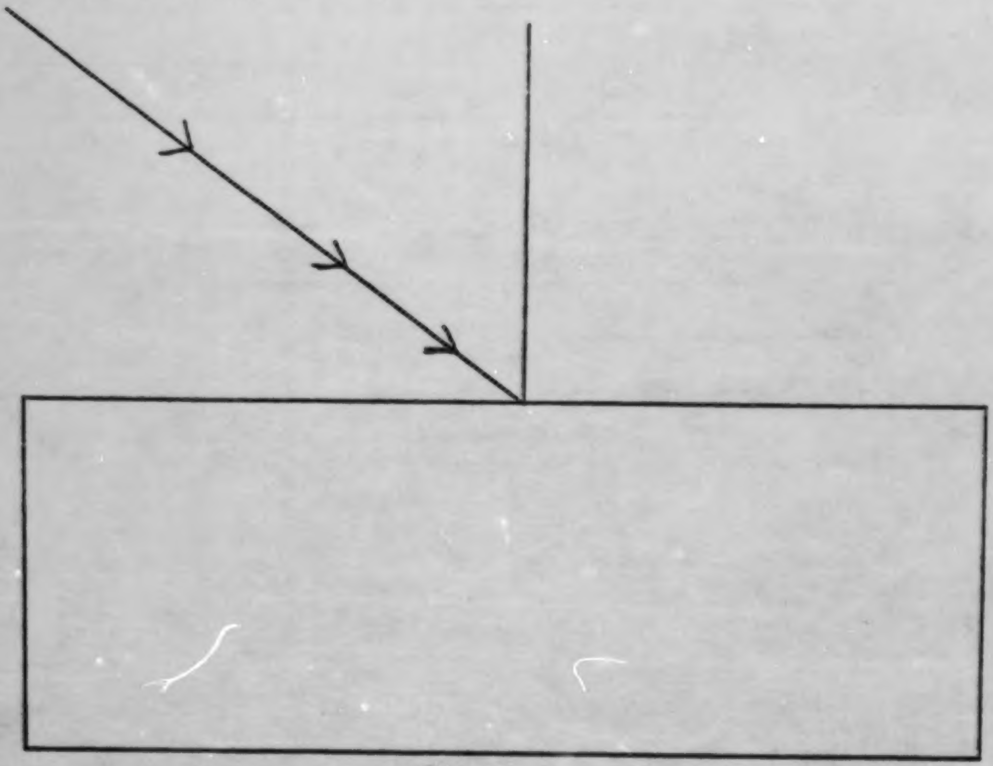


Figure 1

a. According to your drawing, how does the direction of the incident ray compare with the direction of the ray leaving the glass?

____

b. How did the lines you drew using Snell's Law compare with the lines you got using pins?

2. Using your understanding of refraction, explain your answer to Question 2 under the Exploration section on Page 498.

3. The index of refraction of a stubstance is a characteristic physical property of that substance (a property that can be used to identify the substance). A scientist seeks the identity of a certain liquid. By refractometric analysis, the incident ray in air is found to be 30.0° and the angle of refraction in the liquid is measured as 27.0°.

a. Find the index of refraction of the liquid.

b. Once the scientist has determined the index of refraction, the possible substances and their indices of refraction must be researched to determine which substances were tested. The following is the scientist's list. Circle the substance you think the scientist has.

Bromine (liq.)	1.66
Chlorine (liq.)	1.39
Hydrogen (liq.)	1.11
Nitrogen (liq.)	1.20
Oxygen (liq.)	1.22

4. The speed of light in a transparent medium is measured at 1.5×10^8 m/sec. If the speed of light in air is 3.0×10^8 m/sec, find the index of refraciton of the medium.

5. Find the speed of light in water and the speed of light in glass using the standard values for each of the indexes of refraction that you were given by your teacher.

6. A ray of light travels through the air, strikes the surface of a substance at an angle of 75° and refracts at an angle of 37°. Find the speed of light in the substance.

Name__________________________

Section________________________

Expansion of the Idea

Part 2: Reading Questions

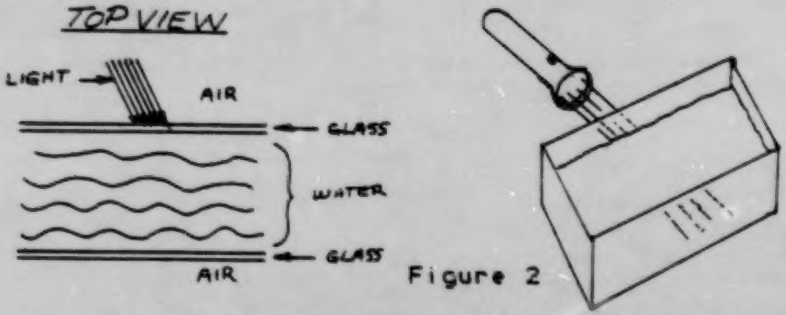


Figure 2

1. A beam of light from a flashlight is directed into a tank of water. The flashlight is placed on one side of the tank. The light must pass through a pane of glass, then water, then another pane of glass and finally into the air on the other side of the tank. If the angle of incident light is 60^{o}, at what angle will the refracted light exit the tank on the other side? Explain your answer (a diagram may be helpful).

2. Your were told in the reading that stars in the sky are percieved as being farther above the horizon than they actually are. Hypothesize an explanation for this phenomenon.

INVESTIGATION 28: REFRACTION OF LIGHT

READING: TALL STARS AND MIRAGES

You know from your work in Investigation 28 that light passing from air into another medium such as water or glass does not follow its original path. Instead, the light rays are bent--or refracted. (The word refraction comes from Latin words meaning to break back.) Refraction is due to a reduction in the speed of light as it passes from air into another medium.

One can determine the refractive index (n) of a certain substance by the equations:

$$n_{\text{medium}} = \frac{\text{sin angle air}}{\text{sin angle medium}} \quad \text{or} \quad n_{\text{medium}} = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}}$$

The refractive index allows us to predict the degree to which the light rays change their direction while passing through a particular material. The greater the refractive index, the more the light rays are bent from their original path. Examine Table I. As the n value increases, the substance is said to be more optically dense. Thus, diamond has a much greater optical density than air or glass.

Table I

Refractive Indices

Material	n*
air	1.003
water	1.330
ethanol	1.360
quartz	1.460
plexiglas	1.510
glass	1.520
polystyrene	1.590
diamond	2.42

$$*n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}}$$

INVESTIGATION 28: REFRACTION OF LIGHT

When light travels from a less optically dense material to a more optically dense material--say, from air into glass--the light rays are bent toward the normal (see Figure 1). On the other hand, when light travels from a more optically dense medium such as diamond to a less optically dense material such as glass, the light rays are bent away from the normal (see Figure 2).

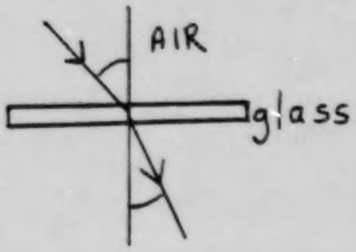


Figure 1

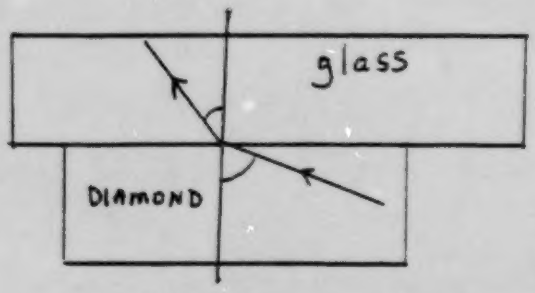


Figure 2

Thus, one could imagine using a combination of media to straighten out a beam of light.

One of the more interesting aspects of refraction is the optical illusions it produces. If you place a stick in water, the stick appears to be bent beneath the water. Fish appear to be larger than lifesize and closer to the surface than they really are. Due to atmospheric refraction, heavenly bodies (stars, not girls) appear to be higher in the sky than they actually are.

Perhaps one of the most intriguing illusions caused by the refraction of light is the mirage. A mirage is a result of the differences in the index of refraction among various temperatures of the air. As the surface material (sand or concrete, etc.) is heated by the sun, the air layer near the surface is heated by conduction. The air a bit further above the surface is cooler. When we look at such a surface from a distance, we see wavy, shimmering lines. This is due to the refraction of light as it passes through varying air temperatures with varying densities. The next time you are driving on hot pavement on a sunny day look down the road. The road may appear to be wet, but it probably is not. The sky seems to be reflected from a wet surface, but the sky's light is actually being refracted through a hot layer of air.

INVESTIGATION 29: LIGHT AND CONVERGING LENSES STUDENT GUIDE

Name__________________________

Section________________________

Introduction

Have you ever used a magnifying lens? If you have, you know that it makes objects look larger. It can also be used to concentrate sunlight to burn holes in paper or to roast ants. These last two activities require that the lens be held a certain distance from the objects to be burned. In other words, lenses bend light and make it focus at specific points and they do all those things because a magnifying glass refracts light.

What relationships are there between the distances from the lens to the object (d_o) and image (d_i). What is the significance of the special distance that makes sunlight most quickly burn a piece of paper? These questions will be answered in this investigation.

Arrange the equipment as shown in Figure 1. You will need to use the lens again later in the investigation, so be sure that you can identify it.

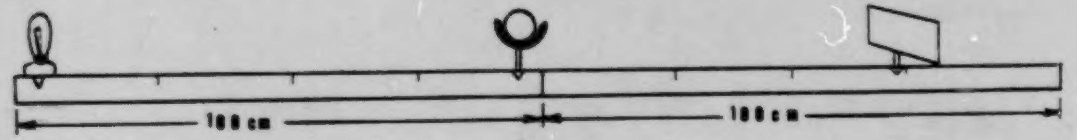


Figure 1

Exploration

1. Gather the data in a darkened room. Place the lens and the light bulb 100 cm apart. Call that distance d_o. Adjust the distance between the lens and the card which is on a second meterstick until you get a sharp image of the lightbulb filament. Measure this distance. Record it as d_i in Table I.

2. For Trials Two through Seven, decrease the distance from the lightbulb to the lens by 15 cm each time (85 cm, 70 cm, etc.) until the lightbulb is 10 cm from the lens. Move the card each time until a sharp image is focused upon it. Carefully measure and record both values, d_i and d_o.

3. For Trials 8 through 11, start with the light bulb 115 cm from the lens and increase the distance 20 cm each trial. Again adjust the card until a sharp, focused image appears. For each trial, record the measurements called for in Table I and whether or not the image is upside down.

Table I

Trial	d_o (cm)	d_i (cm)	Image Erect or Inverted?
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			

5. Return to your seat and make a graph of your data, with d_i on the vertical (Y) axis and d_o on the horizontal (X) axis.

The Idea

6. Describe the shape of your graph.

7. Use your graph to predict d_i if the lightbulb were moved 5 m, 10 m and then to 100 m from the lens. Using your graph, defend your predictions.

8. You have just found the focal length of a lens. Write a description of focal length.

9. Use your graph to find the numerical value of the focal length of your lens. Write that focal length here.

Expansion of the Idea

Part 1: An Experiment

10. You just found the focal length of a lens by plotting data from measurements. There is an alternate procedure to use in measuring the focal length of a lens. To use that alternate procedure, you need to recall the description of focal length you worked out from data on concave mirrors. Write that description here.

11. What, from that description of focal length, might be useful in measuring the focal length of a convex lens?

12. Design a procedure to measure the focal length of a convex lens which used the lens, a screen of some kind--a 3"x5" white card works well--and a meterstick. Describe that procedure here.

13. Earlier, you plotted a graph from the data in Table I and read the focal length from that graph. How do the individual focal lengths measured and their mean compare to the focal length you just measured?

Expansion of the Idea

Part 2: Ray Diagrams

You have just determined that ideas from mirrors can be transferred to lenses. You learned much from drawing ray diagrams for mirrors. Ray diagrams can be used to learn about lenses. Here are some points from mirrors which will be useful in drawing ray diagrams for lenses:

1. Light rays coming from a distant object are traveling parallel
2. Parallel light rays striking a concave mirror are reflected through the focal point
3. From Number 2, we can say that parallel light rays striking a convex lens will be refracted through the focal point.
4. Light rays leave any point on an object in all directions
5. Whenever two light rays cross, an image is formed.

Name__________________________

Section_______________________

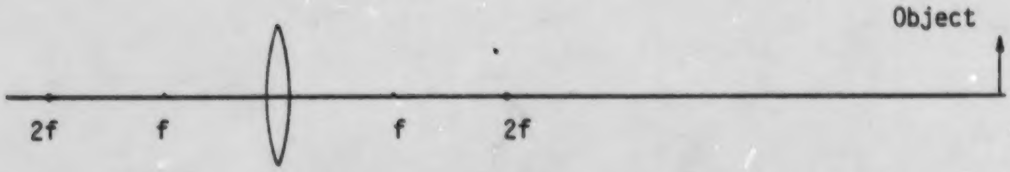

Object
2f
f
f
2f

Figure 2

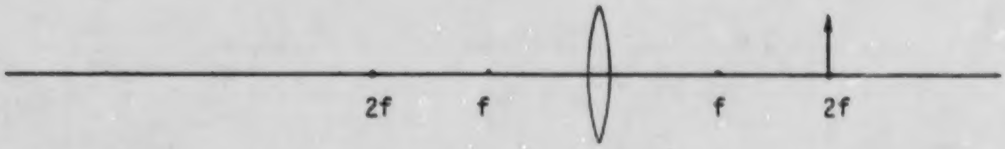


Figure 3

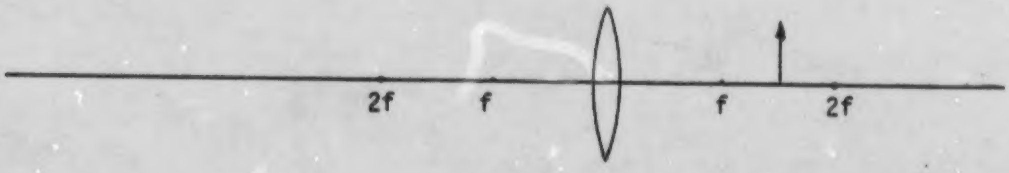


Figure 4

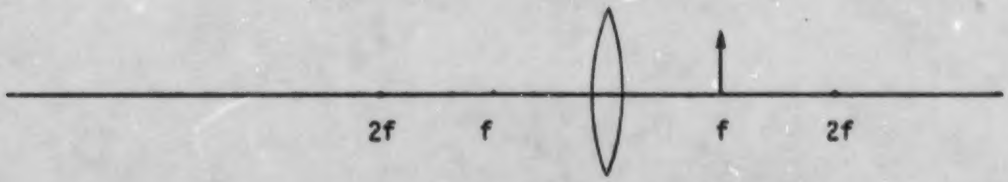


Figure 5

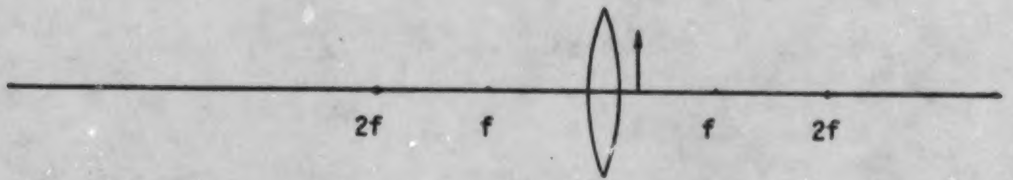


Figure 6

Expansion of the Idea

Part 3: A Geometrical Proof

Consider the ray diagram shown in Figure 7. Using geometry, an important principle of lens can be developed.

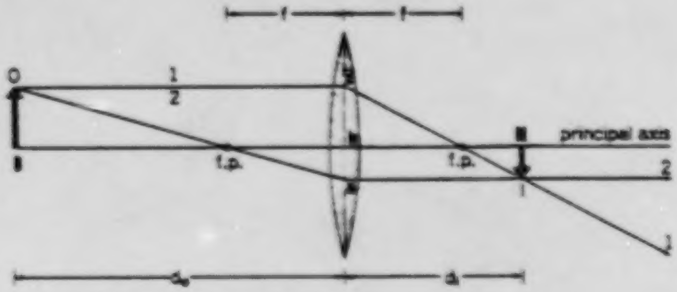


Figure 7

In Figure 7, ab=IM. Therefore, we may draw

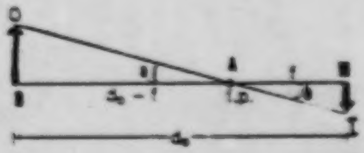


Figure 8

14. Inspect Figure 8. Prove that triangles OAB and IAM are similar triangles. Show that proof in the space below.

15. What relationship involving d_o and f can be written from the similar triangles in Figure 8?

16. Inspect Figure 7 once more. cb=OB. Therefore, we may draw

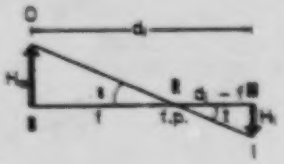


Figure 9

Inspect Figure 9. Prove that triangles ORB and IRM are similar triangles. Show that proof in the space below.

17. What relationship involving d_i and f can be written from the similar triangles in Figure 9?

18. Look at the relationships you wrote in Questions 15 and 17. What do those relationships allow you to say about f, d_o, and d_i? Write your conclusion in the space below.

19. The relationship you just wrote is called the lens equation. Where else have you seen that equation?

Go back to Table I. You know the focal length of the lens you need. Use the d_o values from Table I and calculate the d_i values using the lens equation. Compare the measured and calculated d_i values.

Name________________________

Section_______________________

Expansion of the Idea

Part 4: Problems

1. An object 0.10 meter tall is placed 0.20 meter from a convex lens. A real image is formed 0.40 meter from the lens. Find:

   a. the height of the image, and

   b. the focal length of the lens.

2. An object 2.0 cm tall is placed 4.0 cm from a convex lens with a 5.0 cm focal length. Find the location and size of the image. Give a description in words as well as mathematically.

Name________________________

Section______________________

Expansion of the Idea

Part 5: Reading Questions

1. Briefly explain any important differences between human eyes and cameras (differences in terms of structure or function).

2. What would you do in order to take a photograph of a virtual image?

3. How is parallax useful to you in vision?

4. What is the name associated with the vision problem where the eyeball is too short?

5. Assuming that your eye is average and normal (the distance from your lens to your retina is 1.75 cm), find the focal length of your eye's lens when you look at an object that is 15 cm away (the closest distance at which most people can focus).

6. Again, assuming that your eye is average and normal, find the focal length of your eye's lens as you look at a distant object.

INVESTIGATION 29: LIGHT AND CONVERGING LENSES

READING: EYE SEE!

The human eye is a wonderful organ. It helps you to watch television, study for physics, and will warn you to get out of the hall, even on the days that the assistant principal wears rubber soled shoes.

How is it possible that such a small package (or pair of packages, actually) is capable of so many useful functions? To be honest, it is not at all a complicated process, and is quite similar to your work in Investigation 29.

Structure of the Eye

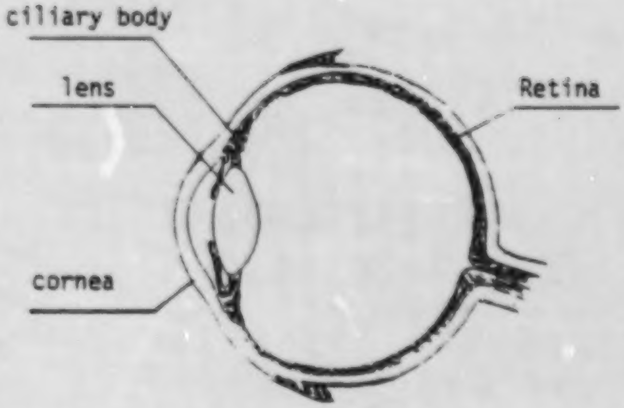


Figure 1

As you can see by Figure 1, there are many parts of the eye, but we will focus our interest primarily on three of them. The retina, which serves the same purpose served by the image screen in the investigation, and is covered with nerve endings to send signals about the picture on the retina to the brain. Next, the lens, which is just what it sounds like, except that it is gelatinous (jello-like) rather than glass. And finally, the ciliary muscles, which wrap around the eye and hold it in place, as well as doing other things which will be discussed later.

Just as in Investigation 29, the light passes through the lens and forms an image on the retina (see Figure 2).

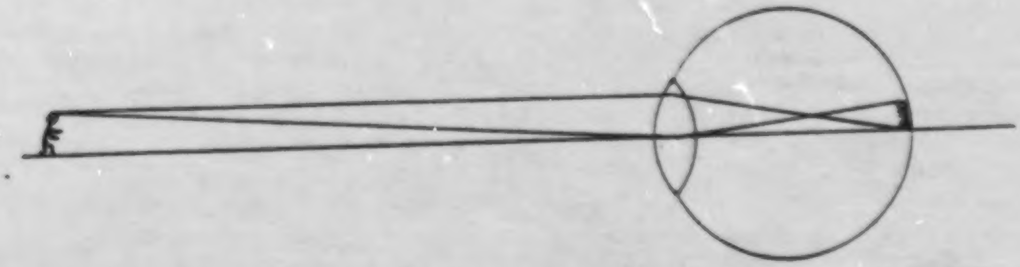


Figure 2

The main difference is that the size of the eye is fixed, and so d_i is fixed, and cannot be changed. (It would not do for the eye to bulge out, increasing it, every time you wanted to look at something close-up. Bulging eyes are reserved for better sights, and rely on a completely different biological mechanism.) The distance from the lens to the retina in the average eye is about 1.75 cm.

When you want to look at an object at a certain distance (d_o), since the image distance is fixed by the depth of your eyeball, the only way that the equation $1/f=1/d_i+1/d_o$ can be mathematically satisfied is for the focal length, f, of the eye to change. You may have noticed during the Exploration phase of Investigation 29, that thicker lenses tended to have shorter focal lengths than thinner lenses (all other things being equal). To change the focal length of the eye's lens, the ciliary muscles tighten up and pull the lens of the eye into a smaller area. This forces the lens to become thicker (the lens material has to go somewhere--it cannot just disappear), changing its focal length. When the muscles relax, the lens returns to its relaxed state which is as thin as it will get and has a focal length approximately equal to the depth of the eyeball (usually about 1.75 cm). The process of changing the lens to allow your eye to focus on objects at different distances is known as accommodation. It will be important later to remember that muscles can only pull, and so the ciliary muscles cannot make the lens thinner than it is in a relaxed condition.

A person with good vision is able to focus on objects anywhere between 15 cm away and an effectively infinite distance, so the eye lens is capable of quite a large range of focal lengths.

All of the foregoing discussion was built around the supposition that the eye is normal and is in good working order. You may wear glasses (more formally known as eyeglasses, spectacles, or corrective lenses) yourself, and if you do not, it is a sure thing that you know someone who does, or should and does not like to be seen in them. What set of conditions could occur that would require a person to add extra lenses to the eye in order to see properly? There are many possibilities, and some of these will be explored, one at a time.

INVESTIGATION 29: LIGHT AND CONVERGING LENSES

The deficiency of sight that seems to be the favorite of comedy writers is myopia, or nearsightedness. The term myopia is Latin, stolen from the Greek myopia, or muops, which means closing or contracting the eyes. In myopia, the image formed by the lens does not focus on the retina, as in normal vision, but it is focused in front of the retina, between the lens and the retina (see Figure 3).

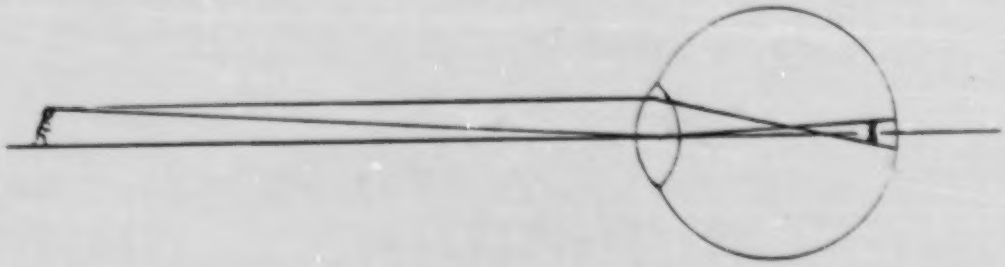
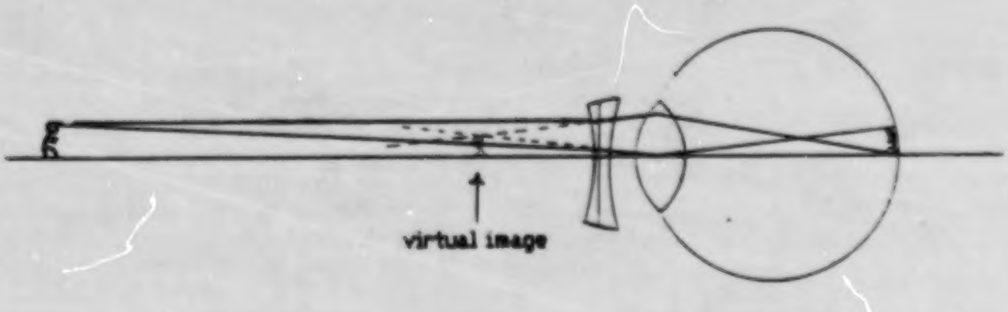


Figure 3

It can be caused by one or both of two things. If the lens is not thin enough in the relaxed state (i.e., it is too curved and has too short a focal length), then the focal point for the lens will be in front of the retina when the object being looked at is above certain distances away. This will cause distant objects to appear fuzzy, and this eye is nearsighted, meaning that the sight is better when objects are near. The other circumstance that could cause myopia would be the case where the lens was normal, but the eyeball itself was too long. This places the image screen of the retina farther away from the lens than it would be, again making the focal length of the relaxed lens too short for the distance involved from the lens to the retina.

Both of these problems can be corrected for by the use of diverging (usually concave or biconcave) lenses. This type of lens provides a virtual image for the eye. Although the image is on the same side of the lens as the object being viewed, it will appear to be closer than the actual object, and will be within the range to which the eye can accommodate (see Figure 4).



This lens is much more curved than any eyeglasses would be. As a result, the image is displaced farther than it would be in real life.

Figure 4

Farsightedness, or hyperopia (Greek: from hyper, meaning over, and opia, from ops, meaning eye), as you might expect, is the opposite condition. Because the lens cannot be made thick enough (to shorten its focal length) by the ciliary muscles, or because of the makeup of the lens, the image forms behind the retina (see Figure 5).

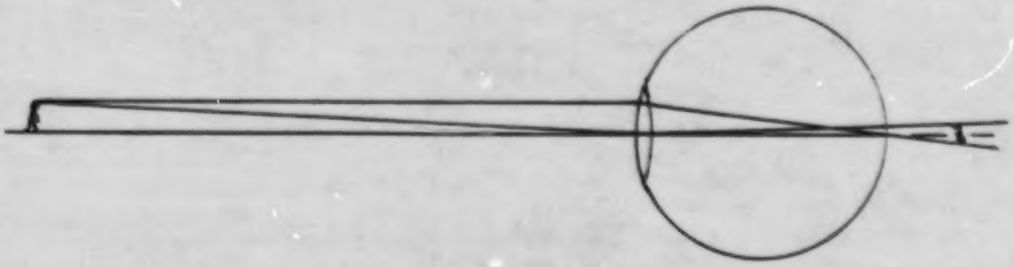


Figure 5

This problem can also be the result of an eyeball that is too short. To correct for hyperopia, converging lenses (usually biconvex, as you used in Investigation 29) are used, to place the rays coming to the eye closer together so that they will focus a shorter distance (see Figure 6).

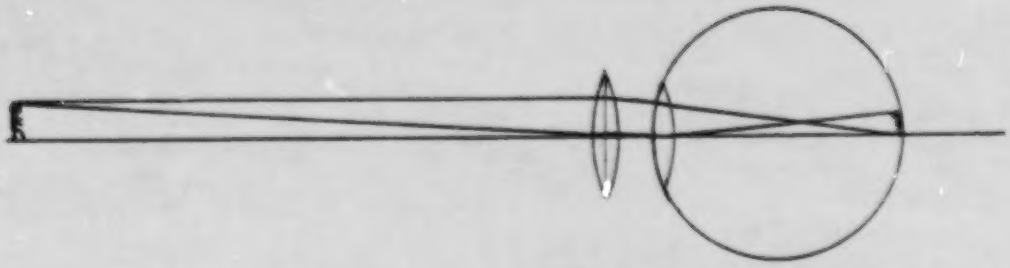


Figure 6

Presbyopia (presbus, meaning old man) is a different condition from hyperopia, but the effect is similar. The lenses of the human eye are susceptible to hardening with age, and are less able to accommodate to as great a degree when they harden. The first sign of this is a loss of ability in the eye to thicken the lens (shortening the focal length) for close vision.

As the lens becomes even less flexible, it can focus only in a limited range of focal lengths, and it becomes necessary for a person to wear bifocals or trifocals (in extreme cases, quatrofocals are used), so that objects at varying distance ranges can be seen clearly. Bifocal eyeglasses are eyeglasses in which different areas of the glass are actually different lenses, and have different focal lengths (trifocals have three focal lengths, quatro- four, etc.).

Astigmatism is a different type of problem altogether. Some lenses are not radially symmetrical, and are said to be astigmatic. This means that a dot would give an image resembling a line more closely than a dot, or a generally fuzzy image in this type of problem. Lenses with structural problems such as this (as opposed to problems in function of the lens or structural problems of the eyeball, as discussed earlier) are said to be abberant, or to have abberations. Persons with astigmatism will have trouble focusing their eyes over a wide range of distances (although it is not uncommon to have astigmatism to some degree with other problems, such as myopia or hyperopia). Astigmatism can be corrected by the use of toric cylindrical lenses, which compensate for the lack of symmetry in the lenses of the eye.

INVESTIGATION 29: LIGHT AND CONVERGING LENSES

So many people wear eyeglasses or contact lenses, the old cry of four-eyes is rarely heard. If it is, however, you now know enough to counter the insult with "My vision is characterized by myopic astigmatism, and is corrected through the use of biconcave toric lenses." (Or whatever your deficiency and prescription are.) "In fact, I probably see better than you do." If it does not get you punched in the nose, it may shut them up.

READING: CAMERA SEE, MONKEY DO

If you were asked to name the first object that came to mind that used a lens or lenses, the object you would probably name first would be a camera. The basic principle of a camera is very similar to the functioning of the human eye, but with some important differences.

Both the camera and the human eye use lenses to form images of objects, which are then focused on image receivers. In the human eye, the image receiver is the retina, which contains, among other things, nerve endings leading to the brain. Light falling on these nerves activates them, they send a signal to the brain, and the brain puts all of the signals (from the millions of nerve endings in your retina) together to form a picture in your mind. Actually, your eyes do not see, your brain does! In a camera, the image receiver is the film (in a still picture or movie camera) or the image tube (in a television camera). Film for a camera is a thin piece of plastic or plate of glass treated with a light sensitive chemical (silver bromide, chloride, or iodide), which will react more or less completely with different amounts of light. With correct processing, the sheet will show a negative image of how it was exposed: areas that received more light will have reacted more completely and thus be darker on the negative, and images receiving less light will have reacted less completely and show up as lighter on the negative. Film for cameras is most commonly found in rolls, but is also available in sheets.

INVESTIGATION 29: LIGHT AND CONVERGING LENSES

Television cameras operate in a manner which is much more similar to the eye than photographic cameras. The image is focused on a screen very similar to a television viewing screen which operates in reverse, compared to a t.v. viewing screen. Electronic detectors convert the light falling on the different areas of this screen into electrical impulses, which are then relayed to the transmitter and broadcast.

Focusing the image on the film, retina, or screen also is accomplished differently in cameras and eyes. As was explained in the previous reading, the eye focuses the image at a fixed distance, because it cannot change size to adjust to different object distances. To do this, the lens changes shape, altering its focal length until the equation $1/f=1/d_o+1/d_i$ is satisfied. In a camera, the lens is made of inflexible material (usually glass), and so this type of adjustment is not possible. To place the focused image on the film, since the object distance is not under the photographer's control and the focal length of the lens is fixed, the image distance must be variable. The lenses of many cameras are therefore mounted so that their distance from the film can be changed to achieve the sharpest image.

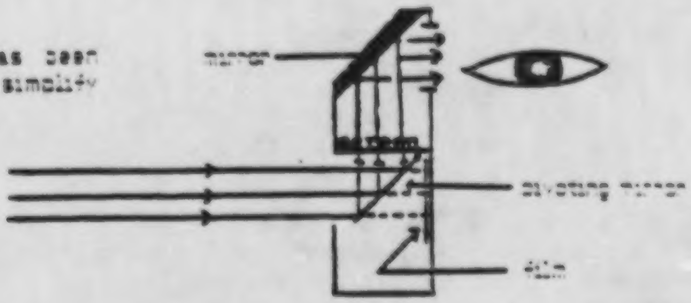
Cameras of today use lenses of many shapes and sizes, but they didn't always. The first camera was the camera obscura, and the early camera obscura had no lenses. Camera is a Latin term meaning room, or chamber, and obscura is also Latin, meaning dark. Thus, camera obscura literally means dark chamber. And that's exactly what it was.

Used by scientists as early as the 13th century, the original device consisted mainly of a darkened box the size of a small room. The box was constructed so that when light entered the box through a pinhole in one wall, objects in front of the box would cast an image on the opposite wall of the box. Artists and astronomers found the camera obscura very useful in studying the projected images of landscapes, celestial bodies, and other objects. The user actually stood inside of the camera, studying the image and taking measurements. There were, however, problems; the pinhole tended to give a very blurry, indistinct image, and had to be so small (to get an image to form) that it tended to produce a very dim image. These problems limited the usefulness of the camera obscura until 1550, when the Italian scientist Geronimo Cardano discovered that a much sharper, brighter image could be formed if a convex lens was placed in the hole through which the light entered.

INVESTIGATION 29: LIGHT AND CONVERGING LENSES

Simple box cameras follow the same basic design as the camera obscura, with a single lens, and a fixed distance between the lens and the film (with a good approximate focus through a wide range of object distances). Simple cameras have many advantages. Since they have little or no provision for adjustments, they are simple to use (just point and shoot) and inexpensive to manufacture and buy. Some lower-priced models of these cameras even use plastic lenses.

More complicated cameras include more convenience and performance features, but follow the same principles. They are also more difficult to operate correctly, providing more opportunities to make mistakes. The most common of the more complex cameras is the reflex camera. The name reflex is derived from reflection, which is how these cameras let you see what picture you will be taking. Light enters the camera through a lens and strikes a mirror, usually placed at 45° (see Figure 7).



The lens has been omitted to simplify the diagram.

Figure 7

The reflected light focuses on a ground glass screen (glass that has been treated so that it will act as a screen rather than as a window), which is just as far from the lens as the film to be exposed is. The photographer then sees what is projected on the ground glass by looking directly at it or by seeing its reflection in a mirror or prism. When the image on the screen appears focused, the image on the film will also appear focused.

INVESTIGATION 29: LIGHT AND CONVERGING LENSES

There are two principle types of reflex cameras, single lens reflex (SLR), and twin lens reflex.

The SLR camera is very popular with photojournalists, scientists, and many amateur photographers. The mirror is placed between the lens and the shutter and the photographer looks into the viewfinder, which provides an image exactly as it will be presented to the film.

Try the following mini-experiment: hold your hand in front of your face, about 20 cm, with one finger raised. Use your other hand to cover first one eye, then the other eye. The shifting of your finger back and forth as you move your hand is known as parallax. Many cameras have difficulty with parallax, because the viewfinder is not in the same place as the lens that will provide an image for the film. Single lens reflex cameras, because the photographer sees what the film will record, do not share this problem. SLR cameras do have a disadvantage, however. Since the mirror is between the lens and the shutter, it must be moved out of the way before the actual picture can be taken. When the shutter button is pushed in a SLR camera, a complex series of events occurs.

First, the mirror swings up, toward the ground glass screen, out of the path from the lens to the film. Next, the shutter opens and closes, followed by the mirror dropping back into place. This can cause problems if the motions of the mirror are jerky, because they might move the camera at the precise time that it should be steady. Also, the mirror is a moving part, and moving parts tend to break down. Further, if the mirror does not return to exactly the same place following the picture being taken, the lens-mirror-screen distance might be different from the lens-film distance, causing images which were focused on the screen to be blurred on the film, or the image might not reflect to the screen at all.

Twin-lens reflex cameras solved the problems associated with a moving mirror by using cameras built with pairs of lenses. One lens provides an image which reflects to the ground glass screen, the image will also be focused when it reaches the film. Twin lens cameras do, however, have the problem of parallax (which is more of a problem in close picture taking than in distance shooting), and they are expensive. Every time a twin lens camera lens is built, it must be built in tandem, with two lenses.

INVESTIGATION 29: LIGHT AND CONVERGING LENSES

Most SLR cameras are know as 35 mm cameras, referring to the fact that the film used is 35 mm wide. The great majority of these cameras have a frame size (the actual size of the exposed area of film) of 24X36 mm.

View cameras are used mainly by professional photographers, and are not common. In general, view cameras do not have a separate viewfinder. Most of these cameras use sheets of film or treated glass plates rather than rolls or film, and to focus the image, the photographer opens the back of the camera and inserts a ground glass plate in the place where the film will be. When the desired image is obtained, the photographer closes the camera back, inserts the film, and takes a picture. View cameras also are flexible, so that the photographer can achieve unusual effects by making the distance from the lens to the film different on one side of the image than it is from the other side of the image. This is achieved through the use of a light-tight bellows, which can be moved from the normal orientation (where the film and the lens are in parallel planes).

Instant cameras, where the pictures develop immediately and without laboratory processing are also in use. These cameras can be any type, and many photographers use instant film packs (on special adapters) on SLR and view cameras to check for proper lighting and composition before taking large numbers of pictures on regularly developed film. This procedure could save costly reshooting by the photographer's noticing unfavorable conditions before the large bulk of film is developed.

Camera lenses are also quite varied. Normal focal length lenses, of about 50 mm focal length for 35 mm cameras, are the most common, but there are many other types. A normal lens gives an image of regular appearance, that is a rectangular or square replica of what you would see with your eye of one section of your field of view.

As a contrast, wide-angle lenses form images on the same size film, but of a greater section of the field of view--a wide angle. In order to do this, they necessarily compress the incoming light rays from an object to fit into less area of the film than they would in a normal representation.

Telephoto lenses do just the opposite. Onto the same size of film, they project an image of a smaller field of view than would a normal representation, by causing the light rays incoming from an object to strike the film farther apart than they would in a normal representation. This produces larger pictures of distant objects than could be achieved with a normal lens.

Zoom lenses have several lens elements, as do many of the other types of lenses, but, rather than being fixed in relationship to other elements, the elements of a zoom lens are movable, which changes the effective focal length of the lens. Two types of zoom lenses are more common than others: telephoto zoom lenses, which can range from moderate focal length to large focal length, and middle-range zoom lenses, which range from moderate wide-angle properties, through normal focal length, to moderate telephoto properties.

To more fully explain the interaction of light with objects, including lenses, one more phenomenon must be explored, and that is the topic of the next investigation.

INVESTIGATION 30: WAVES STUDENT GUIDE

Name________________________

Section______________________

Introduction

If you throw a stone into the middle of a pond or puddle, a circular wave moves out from the point where the rock hit the water. The wave grows rapidly in diameter while diminishing in height until it disappears.

The next several investigations will be devoted to giving you the opportunity to study waves.

You will need a ripple tank. It provides a layer of shallow water over a glass plate through which you can shine a light and record observations on paper about the water waves, below. The light should be securely mounted above the ripple tank. You should also have a rubber hose or curved metal piece, a long piece of wood, and a ruler.

The ripple tank should contain water of a depth of 6 to 8 mm. Check the corner depths to see that the tank is level.

As you make observations, it will be important that you keep records and drawings of what you have done and what has happened, so keep pencil and paper available.

Exploration

1. You can make waves by dipping your finger or a pencil eraser into the water. What is the shape of the pattern formed by these waves?

   ____

2. You also can make waves by putting a ruler into the water, then raising and lowering it or moving it back and forth. What is the shape of the pattern formed by these waves?

   ____

3. Using the materials you have around your ripple tanks, make and record other observations about waves in your ripple tank. Be ready to share your observations later with the rest of the class. Use the rectangles below to make drawings of what you see in the ripple tank as you produce waves.

4. Now make a small paper boat that will float on the water in the ripple tank. Put it on the water in the middle of the tank. Send several waves, one at a time, toward the boat and record your observations as the waves reach and pass the boat.

5. Now stretch a slinky to no more than 8 meters. Slinkies are easy to tangle, but difficult to untangle, so handle them carefully.

   a. See if you can duplicate, using the slinky, some of the observations you made with the water in the ripple tank. Record your observations here.

b. Place an object, like a small box, alongside the slinky and send a wave by it. Describe what happens to the object.

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The Idea

6. Explain and interpret the observations you made with waves. Begin with the boat and the box. You know that when something is accelerated through a distance, work is being done on it, and when work is being done, energy is being used.

   a. How do you know that work is being done on the boat and the box as a wave passes by it?

   ____

   ____

   b. What is the source of the energy moving the boat and the box?

   ____

7. Give a description of a wave which explains the observations you have made, including your experience with the boat and the box.

Name________________________

Section______________________

Expansion of the Idea

Reading Questions

1. How can surfing be considered conversion of energy from waves?

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2. If every home in Japan has ten one-hundred watt lightbulbs in electrical sockets, how many Japanese homes could be lighted continuously by the Japanese experimental station? (Assume no loss of energy in delivering the electricity to the homes).

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3. In the British raft generator, what changes in form does the energy have between wave energy and electricity?

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4. According to the information in the reading, how much energy in the form of electricity should be provided by one raft 50 yards wide placed in the North Atlantic near Scotland?

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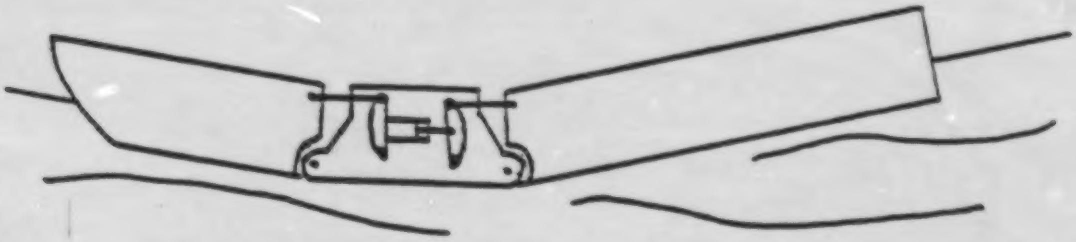
READING: ENERGY FROM OCEAN WAVES

If one had not been convinced that waves are energy moving through a medium before this investigation, he would merely have to have thought of a surfer capitalizing on the waves approaching the Hawaii coastline. The wave moves the surfer at speeds up to fifty miles per hour as he uses his ability to draw energy from the wave.

The question then comes to a person who considers seriously the energy crisis, why not make use of energy from wave power? One might think of himself as the first to verbalize that idea until he realizes that attempts to harness wave power are already being carried out.

In August of 1977, the Japanese set up an experimental station 2 1/2 miles off Honshu Island. It weights 500 tons and produces 125 kilowatts of electricity, which is 125,000 joules of energy per second. The system operates because of floats inside open-bottomed chambers which bob up and down forcing air through nozzles in the top of the chambers which in turn drives electric generators.



Another system of flexible-jointed rafts, developed in Britian by Sir Christopher Cockerell, employs double-acting hydraulic cylinders which pump hydraulic fluid to a hydraulic motor which drives an alternator. A general sketch of the idea is shown above. The project began with a trial rig ten yards long and five yards wide located in a protected channel. It is only 1/10 the size of the actual models planned for positioning in the North Atlantic where the waves are about ten times larger. The trial raft has an average energy output of about 1000 joules every second (or one kilowatt of power) at an energy-conversion efficiency of about 50%. The raft also employs the use of an hydraulic accumulator between the hydraulic pumps and the motor which smooths out the flow and provides a nearly constant pressure and therefore voltage. The electricity is carried by sunken cable to the shore.

Cockrell hopes to someday have a series of rafts in the North Atlantic near Scotland where each yard of approaching water could provide sixty kilowatts of power. The rafts placed there would be fifty yards wide.

INVESTIGATION 31: WAVES AND BARRIERS STUDENT GUIDE

Name________________________

Section______________________

Introduction

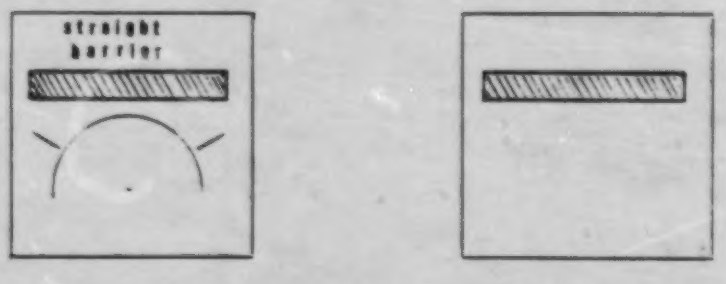
In the section on light, you observed what happens to light when it is directed toward mirrors and through lenses. In this investigation, you will be directing waves toward obstacles and observing the resulting waves.

Again, you will need your ripple tank, a straight barrier, a curved barrier, a ruler or straightedge, and two small barriers. You will also need a slinky, a heavy coil spring, and an object shaped like a cross-section of a double convex lens.

Exploration

1. Using a ruler, make a straight wave in the ripple tank. The wave should travel straight across the tank. If the wave bends or veers to one side, the water is not the same depth throughout the tank. Correct that problem, then continue.

2. Place a long piece of wood in the middle of the tank and generate a circular wave toward it as shown in the diagram. We will call the long piece of wood a straight barrier.



Before After

Figure 1

3. Make and describe a drawing of what happens to the wave after it reaches the straight barrier.

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Repeat the process several times until you are sure that what you have described has occurred.

4. Now repeat what you did in Step 2, except send a straight wave toward the straight barrier.

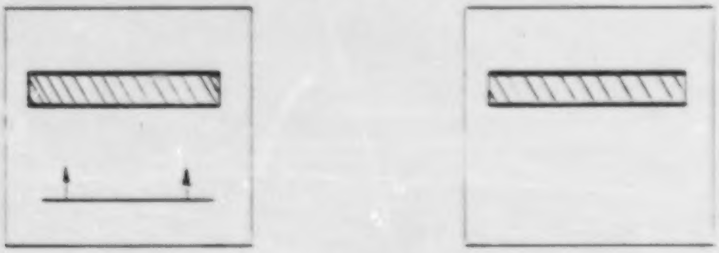

Figure 2

Draw and describe what happens to the straight wave after it reaches the barrier.

5. In Step 4, the barrier front should have been parallel to the straight wave moving toward it. Now, change the position of the barrier so that the barrier front makes an angle of 10° with the incoming straight wave.

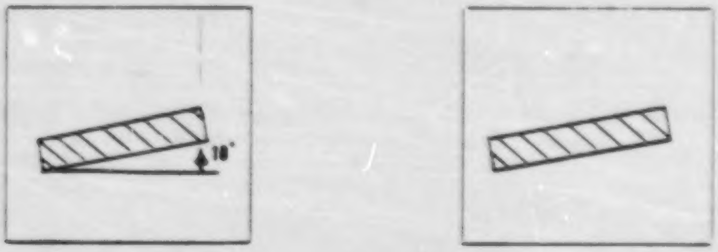

Figure 3

Carefully observe what happens to the wave aftger it reaches the barrier. At what angle does it leave the barrier with respect to the barrier front?

6. Now change the barrier angle to 20°

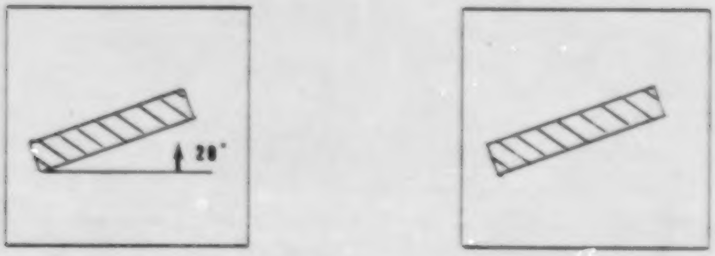

Figure 4

At what angle does the wave leave the barrier?

7. Now change the barrier angle to 30°.

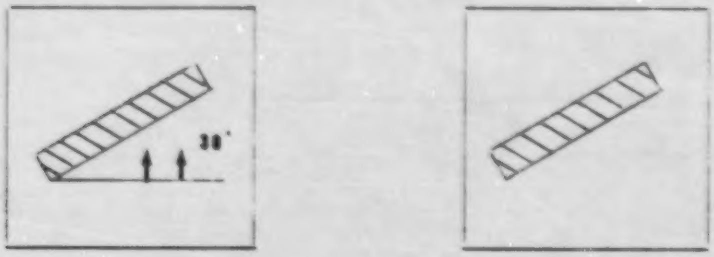

Figure 5

At what angle does the wave leave the barrier?

Be prepared to put your data on the chalkboard or overlay according to instructions from your teacher.

8. Now put the curved barrier into the water. This is the rubber hose (shaped like a parabola) or the curved metal piece. Arrange it as shown in the diagram.

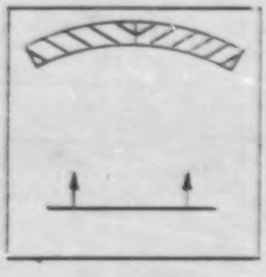

Figure 6

9. Send a straight wave toward the barrier and observe what happens aftger the wave reaches the barrier. After repeating this process several times, make a drawing and describe what happens.

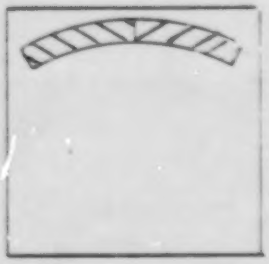

Figure 7

10. Send a circular wave toward the barrier. Start it at the point where the reflected waves met (converged) in Step 9. Make a drawing and describe what happens.

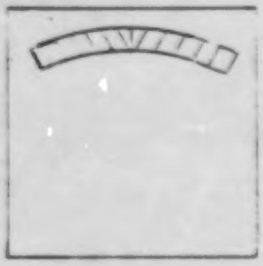

Figure 8

11. Start a circular wave about half-way between the middle of the barrier and the convergence (or focus) point you found in Step 9. Make a drawing and describe what happens.

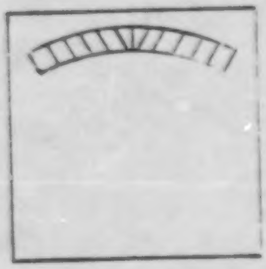

Figure 9

12. Start a circular wave about twice the distance from the middle of the barrier to the focus. Make a drawing and describe what happens.

The Idea

13. Compare what you observed when you sent a circular wave toward the straight barrier in Step 2 with the reflection of light from a plane mirror.

14. Compare the angle of incidence of a wave moving toward a straight barrier with the angle the wave leaves the barrier.

15. How does your description of reflection of waves from a barrier compare with the law of reflection for light you made in earlier investigations?

16. Compare the observations you made in Step 9 (with the curved barrier) with the data you collected using the curved mirror in the light section of this course.

17. Compare the observations you made in Steps 10, 11, and 12 with the data you collected in the curved mirror investigation.

18. Based on the data you have collected in this investigation and the comparisons you have made above, compare the behavior of waves and light.

Name________________________

Section________________________

Expansion of the Idea

Part 1: Refraction

According to the evidence you have collected so far, waves and light behave similarly. We will now assume that waves and light will behave similarly in other situations as well and test to see whether or not our assumption is upheld by experience.

1. Again, you will need the ripple tank for this part of the investigation. Lay a glass plate (or two) in the water at the middle of the tank in order to make an area of shallow water over the glass. The water over the glass should be no more than 2 mm deep compared to 6 or 8 mm in the deeper part of the tank. The front edge of the glass should be parallel to straight waves moving toward it. Using your ruler, make a straight wave that moves toward and over the glass plate.

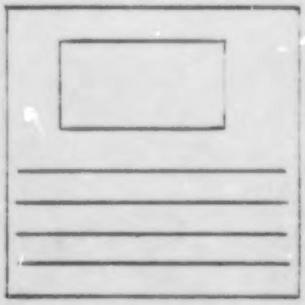

Figure 10

Describe and make a drawing of what you observe as the wave reaches and passes over the shallow water. Repeat the process until you are certain that what you have written describes what happens when the straight wave reaches and passes over the glass plate.

2. Now change the position of the glass plate(s) so that the front edge of the glass makes an angle of about 30° with the waves coming toward it. Send straight waves toward the shallow water. Make a drawing of and describe what you observe as the waves reach and pass over the glass plate.

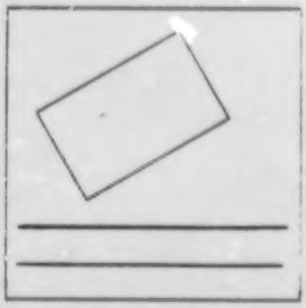

Figure 11

3. Connect a slinky to a heavy coil spring and have your partner step back until the slinky is stretched about eight meters. Do not stretch the slinky more than eight meters even if the heavy coil does not appear to be stretched. Send a pulse along the slinky and watch what happens when the pulse reaches the junction between the springs. When any of the pulse crosses the junction into the other spring, we will call that refraction.

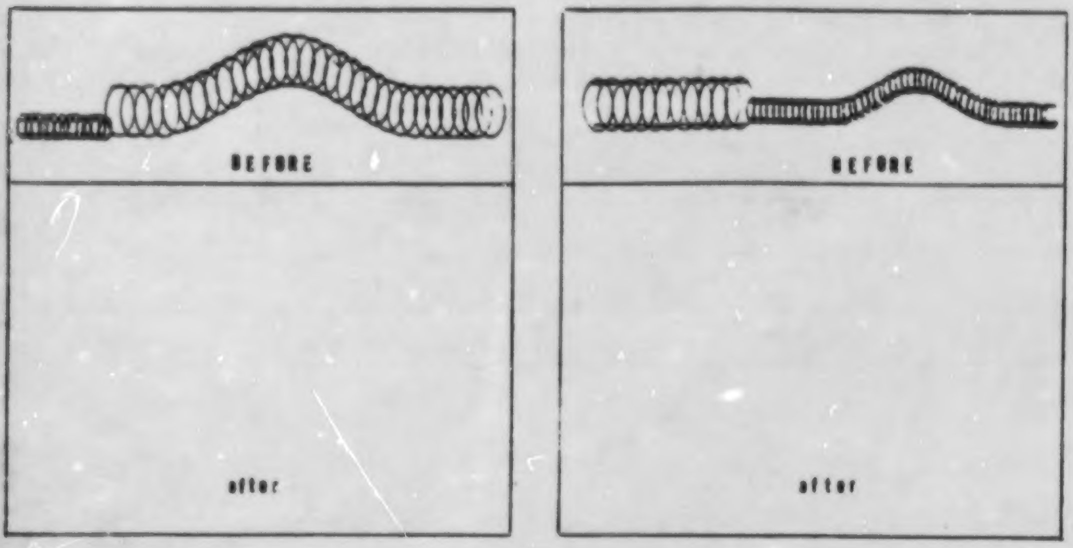

Figure 12

Record any reflections and refractions that you observe.

4. You should have an object shaped somewhat like the cross-section of a double convex lens. Place it into the water so that shallow water is above it and send straight waves toward the lens-shaped shallow water. Make a drawing of and describe what you observe as the wave reaches and passes over the shallow water.

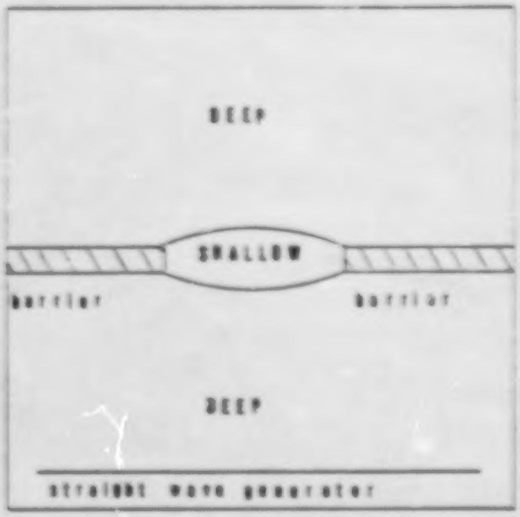

Figure 13

5. Based on the observations you have just made, how valid is the statement, "Waves and light behave similarly, when applied to refraction."

Name______________________

Section______________________

Expansion of the Idea

Part 2: Diffraction

1. Place a wooden block in the tank as shown in the drawing at the right. The block should not be completely submerged. Draw and record what happens as the waves reach and pass the block.

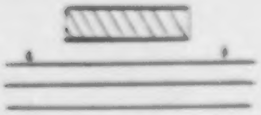

Figure 14

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____

2. How much wave shadow (water having no waves) is there behind the block?

____

The bending of waves around objects in their path is called diffraction.

3. Place two blocks in the ripple tank making a two inch opening as shown in the drawing at the right. Draw and record what happens as the waves pass the opening.

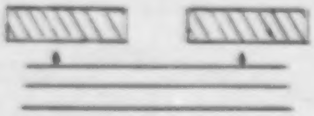

Figure 15

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4. How does light behave when it encounters an object or an opening between two objects (a slit); does it leave a distinct shadow or reveal a high degree of diffraction? (If you do not know, try shining light around an object or through a slit.)

____

Explain your answer.

5. What can you say about the similarity of waves and light from your observations of diffraction?

6. Attach the motor system on your ripple tank so that you can produce repeated straight waves (called periodic straight waves). You should also have a variable rheostat (resistor) so that you can vary the rotation rate (frequency) of the motor. Repeat Steps 24 and 26 using periodic staight waves. Gradually increase the frequency of the motor. Repeat Steps 1 and 3 using periodic straight waves. Gradualy increase the frequency of the motor and observe the effect on the diffraction of waves passing by or through the obstacles. Record that effect in the lines and on the drawings provided. Paticularly note the amount of diffraction when high frequency waves are directed toward the obstacles.

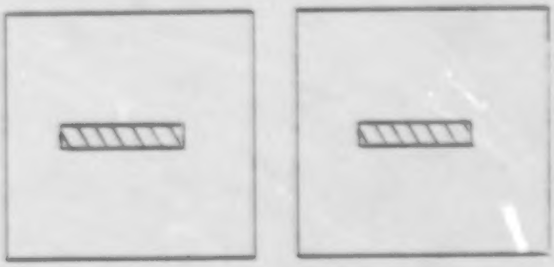

Figure 16

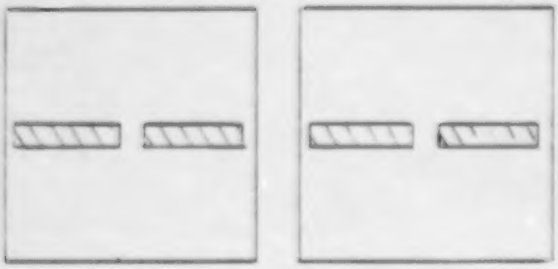

Figure 17

7. How does what you did in Question 6 affect your answer to Question 5?

8. You may want to try sending periodic straight waves toward shallow water areas and the double convex shallow water region that you used earlier with only single waves. Draw diagrams of these systems in the space below.

Name____________________

Section____________________

Expansion of the Idea

Part 3: Problems

1. Predict the angle which the barrier should have relative to the incident wave such that the reflected wave front is parallel to the side of the tank. See the diagram.

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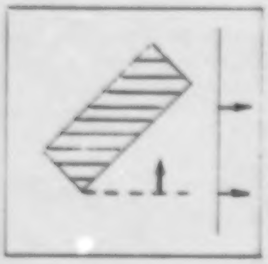

Figure 18

Test your prediction by placing the barrier at the predictged angle and sending a straight wave toward it.

2. In the drawing, a straight pulse approaches a right angle barrier at an angle of 45°.

   a. How will it reflect from the barrier?

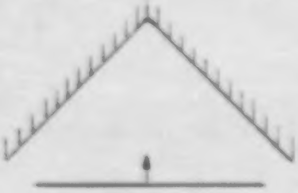

Figure 19

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   b. Explain your answer to Part a.

____

____

3. Is diffraction a wave phenomenon or does it also occur when moving objects pass through small openings or near obstacles?

____

____

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4. The drawing at the right shows straight waves being refracted as they encounter a shallow water area. Since wves and light behave similarly, use Snell's Law to determine the index of refraction rom the deep water medium to the shallow water medium.

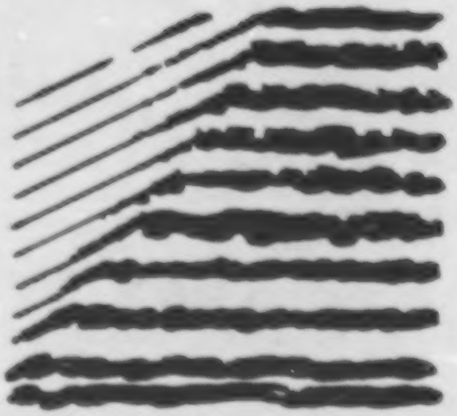

Figure 20

5. Discuss with your classmates what might cause the following two wave patterns to appear. Then write your conclusions below the drawings. Also, you may with to test your ideas with the ripple tank.

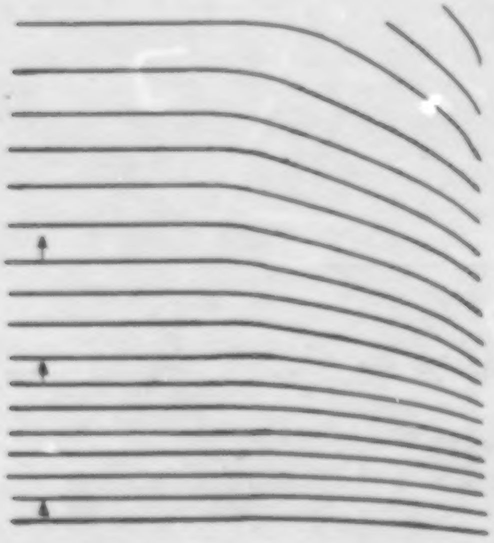

Figure 21

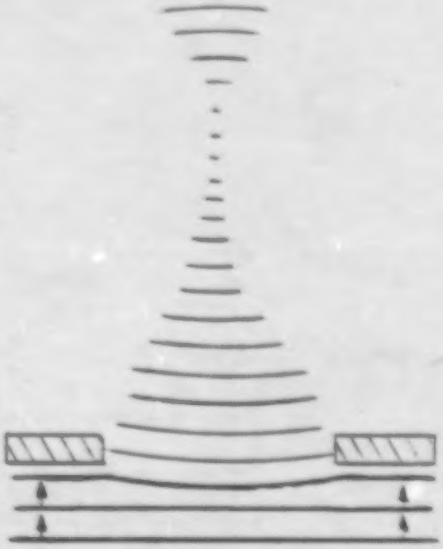

Figure 22

Name____________________

Section____________________

Expansion of the Idea

Part 4: Reading Questions

1. List three kinds of waves discussed in the reading.

2. A statement in the reading, Other Waves, reads, "Normal pitched talking sounds have wavelengths of one-half to three meters, which explains why talking sounds are diffracted well through doors and windows." Based on your data and the idea of diffraction from Investigation 31, why are the sounds described diffracted well through doors and windows?

3. What wave ideas make sonar useful for judging depth of water?

4. In exploration seismology, what wave ideas reveal the subsurface geologic structure?

5. How is FM radio different from AM radio?

6. How are microwaves, generated by the magnetron, spread so they fill the microwave oven?

____

____

7. Why are X-rays used to study inter-molecular distances by X-ray diffraction?

____

____

READING: OTHER WAVES

Now that you have had experience with water waves and waves in slinkies and coil springs, it is time to mention other kinds of waves with which you may be familiar (and some you may know little about).

You have heard of sound waves. These are longitudinal disturbances which pass through the air. They may be shock waves such as the clap of someone's hands or the thunder of a distant explosion. They may be periodic waves of a frequency that you interpret to be the hum of a motor or a musical note. If you stand some distance from a wall and clap your hands, you will hear the reflection which we call an echo. Wavelengths of sounds you can hear vary from almost six meters (for very low-pitched sounds) to two centimeters (for very high-pitched sounds). Normally pitched talking sounds have wavelengths of one-half to three meters which explains why talking sounds are diffracted well through doors and windows. Sound waves do refract also, but it is difficult to set up conditions to experience sound refraction.

Sound also travels through water. In fact, it travels faster through water than through air. Sonar systems have been developed which determine the depth of water by using an echo from the bottom. These systems are added to the boat equipment. They measure the time for a wave from the boat or ship to echo from the bottom and use the speed of sound in water to determine the depth. When the water depth is less than ten feet, the meter may show a strong signal at the proper depth mark and a weaker signal at twice the depth. This happens because the echo reflects from the boat to the bottom and returns to be registered again on the boat's meter. In the sea, false echoes are known to return from whales and submarines passing below the ship.

Radar is another wave system used in meterology and police work. Echoes from rain storms reveal their distance from the source of the radar. Modern meterologists also use Doppler radar to tell how fast storms are moving, just as police use the same type of radar to determine the speed of motorists. Doppler radar works on the principle that moving objects return a signal of slightly different frequency than that of the signal sent. If the object is moving toward the source of the radar, the echo will have a frequency higher than the sent signal. An object moving away will return a signal of lower frequency. The change in frequency depends on the speed of the moving object relative to the source of the radar.

INVESTIGATION 31: WAVES AND BARRIERS

The earth can serve as the medium for waves, known as seismic waves. Exploration seismology uses seismic waves to determine the subsurface geologic structure. Waves sent out by explosions near the surface are reflected from subsurface layers and reveal probable locations of oil and natural gas.

A large group of waves which has proven very useful through modern technology are the electromagnetic radiations. These radiations include electric waves, radio waves, infrared rays, light, ultraviolet radiation, X-rays, and cosmic rays. They are listed in order of increasing frequency and decreasing wavelength.

Electric waves are commonly produced in electric currents by microphones. Microphones change sound waves to electric waves. The sound waves can be recovered by running the current-carried electric waves through an electronic speaker. The wavelengths of electric waves are from 10^{12} to 10^{6} cm.

In radio stations, electric waves are converted to radio waves by means of transmitting antennas. Radio waves can be transmitted two ways.

When the amplitude of the signal is modulated (varied), the resulting wave is called an amplitude modulation (AM) signal. Many radio stations use this wave method. The benefits to radio stations and their listeners of this type of modulation is that the waves follow the curve of the earth somewhat and they are reflected from upper atmospheric layers back to the earth. Therefore, AM broadcasts can be received far away from the transmitting tower. At night, when the atmosphere changes because the sun's rays no longer affect it, the broadcasts can be received from even greater distances such as across continents.

Another form of wave adjustment is called frequency modulation (FM). In this case, the frequency of the wave is varied and the amplitude remains constant. Frequency modulation does not have the range benefits of AM since it is not reflected by the upper atmosphere. The waves travel straight and do not follow the curve of the earth. Therefore, FM towers are made very tall to obtain the maximum coverage possible. There are some advantages to FM broadcasting. A sound more like the original is produced. Therefore, music sounds better over FM than AM. Another benefit is that electrical storms which produce static on AM broadcasts have little effect on FM.

INVESTIGATION 31: WAVES AND BARRIERS

Radio waves vary in wavelength from about 10^6 to 10^{-1} cm (that is from ten kilometers to one millimeter). Radio waves between 30 cm to 1 mm are a special group of waves called microwaves. Microwaves easily pass through rain, smoke and fog. Therefore, they are good for long distance communication and navigation control. Since they pass through the atmosphere so easily (with such low energy loss) there has been some talk of increasing our solar energy supply by placing solar energy converters into orbit around the earth and beaming the energy to the earth by microwave.

Microwaves have also been used for cooking. If you take a microwave-generating vacuum tube (called a magnetron), rig it to give off microwaves in a rectangular box built of microwave reflecting material such as metal, and add a fan-shaped metal blade to spread the waves by reflection, you have a microwave oven. Microwaves happen to have a frequency that is just right to vibrate food molecules, but not affect glass, paper, or china. The result is that microwaves pass through the containers into the food and heat it. Since the waves are reflected by metal, it will not work to wrap your food in aluminum foil.

Infrared (pronounced in-fra-red) radiation has wavelengths between 10^{-1} and 10^{-4} cm. Objects give off infrared radiation in relation to their temperature compared with the temperature of their surroundings. The greater the temperature difference, the more infrared radiation is given off. Since infrared rays can expose photographic film, infrared cameras have been developed which will take pictures at night. Such cameras may be used to photograph illegal transactions and the movements of people and animals at night. Meterologists photograph large sections of the earth at night using infrared camera-carrying weather satellites. Infrared photographs of your house can show how much heat is escaping compared to your neighbor's houses. Photographs of fields can reveal what kind of crop is being grown. Toasters convert electricity to infrared radiation to toast your bread.

Visible light shows some characteristics of a wave nature, however, we will deal in more detail with its particular characteristics and uses later.

INVESTIGATION 31: WAVES AND BARRIERS

Ultraviolet radiation is given off by the sun and has wavelengths around 10^{-5} and 10^{-6} cm. It is higher energy radiation than white light and is a primary cause of sunburn. Fortunately, most ultraviolet radiation is absorbed by the atmosphere and never reaches the surface of the earth. True ultraviolet is not visible to the human eye, but it can be absorbed by some minerals causing them to emit light that we can see. We say these minerals are fluorescent.

Electromagnetic rays that have wavelengths between 10^{-6} and 10^{-9} cm are called X-rays. These are high energy rays that can penetrate the human body. Some pass through, so photographs of the internal organs can be made with X-ray photography for use in medicine and research. Since diffraction is magnified when split distances are about the same size as the wavelength of waves passing through them, X-rays are the right choice for studying intermolecular distances by X-ray diffraction. The distances between atoms in molecules can be accurately measured by this means and models of the molecule can be drawn or built.

Gamma rays have wavelengths around 10^{-10} cm. They are given off by radioactive materials. These high energy rays are generally harmful to the human body, especially when it is exposed to large amounts of the radiation. Gamma rays can be helpful, though, in treating cancer and in scientific research.

Cosmic rays carry the most energy and have wavelengths between 10^{-10} and 10^{-14} cm. These rays come from outer space. Most never reach the surface of the earth because they interact with atoms in the atmosphere producing high energy elementary particles. Under normal conditions around twenty to eighty clicks per square inch per minute can be registered by Geiger counters due to this background radiation.

INVESTIGATION 32: SPEED OF A WAVE STUDENT GUIDE

Name______________________

Section______________________

Introduction

How fast do waves travel? In this investigation you will be applying your knowledge of speed to find the answer to that question.

Stretch the slinky to 8.0 meters. Send two pulses, one after another. Continue sending such double pulses, varying the sizes of the pulses (such as large, then small; small then large). Also vary the shapes of the pulses (How can you do that?)

1. How does the distance between the pulses change as the pulses move along the slinky?

____

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2. What can you say about the relative speeds of the pulses as they move along the slinky?

____

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3. What effect does quickness of hand motion (in making the pulse) and size of the pulse have on the speed of the wave?

____

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4. Repeat Steps one through three using the long, heavy coil. What can you say about the relative speeds of the pulses of different size and shape as they move along the coil spring?

____

____

____

____

5. Stretch the long heavy coil to 4.0 meters length. Determine the speed of a pulse as it travels along the spring. (Stopwatches are available.)

    a. How will you determine the speed of the pulse in the spring?

    ____

    ____

    b. Make three measurements of the speed and average them. Record your data in Table I.

6. Stretch the slinky to 4.0 meters length. Determine the speed of a pulse as it travels along the slinky and record three measurements in Table I.

7. Now stretch the slinky to eight meters and have someone hold it to the floor at the midpoint (4 meters) so that you have increased the tension in the spring but have kept the distance the same. Again make three measurements of the variables you will need to find speed and determine the speed of a pulse in the four meter stretched slinky. Record your data in Table I.

8. Remove all the barriers and glass plates from the ripple tank, collect the data you need to make three measurements of the speed of a wave through the ripple tank and record your data in Table I.

Table I

Medium	Time (sec)	Average	Distance (m)	Speed (m/sec)
Heavy coil spring				
Slinky Stretched 4.0 meters				
Slinky Stretched 8.0 meters				
Ripple Tank				

The Idea

9. Based on the data which you have gathered and recorded in Table I, how do the speeds of waves compare with different media that are used?

10. According to the data you have taken, which variable determines the speed of a wave?

11. What is the effect of doubling the length of the slinky on the speed of a wave through it?

Name____________________

Section____________________

Expansion of the Idea

Part 1: Questions and Problems

1. An extra long slinky can be stretched to a length of twenty meters. A small pulse is generated followed by a large pulse made with quick hand motions. Assuming both pulses reach the other end, which pulse will reach the other end first? Explain your answer.

2. The slinky described above, while stretched to a length of twenty meters, is anchored in the middle. A pulse takes 2.0 seconds to go from one end to the middle.
   a. find the speed of the pulse described.

   b. A pulse is then started from the other end and its time to reach the middle is measured. How would you expect the speed of the two pulses to compare?

   c. Explain your answer to part b.

3. Could the stretch of the slinky and heavy coil spring be adjusted so that waves passing through them would travel at the same speed? Explain.

4. How could you change the speed of water waves?

Expansion of the Idea

Part 2: Reading Questions

You were told in the reading, Other Waves, in Investigation 31, that sound is a wave phenomenon. Light also has wave characteristics. You know that waves require a medium if they are to be transmitted. Discuss the similarities and differences of the effect of a vacuum on sound and light. (Hint: you might want to think back to the use of the Bell jar in earlier science courses.)

INVESTIGATION 32: SPEED OF A WAVE

READING: THE MEDIUM FOR LIGHT

A debate about the nature of light was going on at the time of Isaac Newton. Christian Huygens argued that light has a wave nature because of the similarities between observable waves and light behavior. There was a problem in Huygen's argument--the problem of medium. The observable waves all have a medium. What, then, is the medium for light waves?

Huygens reached back to the time of the Greeks and pulled out the name aether. To the Greeks, aether meant that which blazes. The term referred to the luminosity of objects in the heavens. Therefore, since no medium was obvious in space, Huygens created one--the aether. The aether (modernized by the shortened term ether) was then the medium responsible for carrying light waves from the stars, sun, moon, meteors, comets, and other luminous objects, to the earth.

In order for the ether to properly explain the behavior of light, it had to have certain properties. Since the speed of a wave depends on the rigidity of the medium (the more rigid, the faster the wave) a speed as great as the speed of light would require a medium more rigid than steel! Yet, in sensual perception, it would have to be no more apparent than a vacuum! Such a combination of properties seemed highly unlikely to many scientists of the time and many to follow, but what else could Huygen's do to save his wave theory for light?

The ether also had to have other properties. Since it was not apparent to human senses (no more than a vacuum) it could not be considered matter. Since a medium carries energy (and is not the energy itself) it could not be energy. Yet it filled all matter and space. The planets could move through it with no effect on their motion. The ether itself, then, did not move with the planets.

The ether became useful to explain other phenomena. For some time, scientists had wondered about how action takes place. They knew Newton's Three Laws of Motion and that actions result from forces, but the question they asked was how these forces were applied. Obviously, they could appreciate direct and indirect action. If you put your hand on an object and push it, the object may move. That is direct action. Indirect action occurs when you take a stick and hit it. It may again move. But some objects can be moved by electricity (combing your hair and then picking up paper with the comb), magnetism, or gravity. The problem was, how is the energy transferred to the object that moves. The motions caused by these attractions had been explained as action-at-a-distance, which really was a way of saying no one knows. Huygens invention of the ether was helpful in that it seemed to give these attractions a mechanism of operation. So it was thought that the ether somehow carried the energy that moved objects by attraction or repulsion.

Ether was gaining respectability among scientists because of its usefulness in explaining observable phenomena. However, problems also began to develop. There were ways in which light and gravity behaved differently. For example, one could reflect light with a mirror, but gravity goes right through it. Light can be refracted, but gravity cannot. Light is absorbed by certain materials but gravity passes right through them. Differences in behavior can also be demonstrated between light and electricity and magnetism. These differences led to considerable discussion about the ether. Some thought the ether idea should be discarded. Others concluded that at least four ethers must pervade all of space. One for light, called the luminiferous (light-carrying) ether, with its specific properties, one for electricity, one for magnetism, and one for gravity. This solution seemed to solve some of the problems but its complexity was unappealing to physicists.

As usual in science when a model becomes too complex, or when several similar observations are explained by separate models, a search begins for unification and simplification. Michael Faraday showed that magnetism could be produced from electricity and vice versa. James Clerk Maxwell put Faraday's observations into what Faraday called heiroglyphics and ultimately showed mathematically that only one kind of ether is needed to carry electricity and magnetism and the electromagnetic radiations so produced would have a speed the same as the speed of light. The unification was too tempting. Light then became an electromagnetic radiation and its wavelength accounted for its specific properties. That implied that there should be other electromagnetic radiations, if Maxwell's unifying mathematical model is correct.

The work of Maxwell and Faraday was a great triumph for the ether model, but the work paid off when in 1888 Heinrich Hertz was able to detect radio waves coming from a low-frequency electric-current oscillator. At that point, there seemed to be no doubt about the validity of the ether model. Soon, other electromagnetic radiations were being discovered. The ether model had proven very useful in finding radiation which would lead to the development of radio and television and other telecommunications equipment. Soon poets were incorporating the ether in their poetry and common people spoke of the ether waves as the reason their radios worked.

More about the ether is still to come.

Name________________________

Section______________________

Introduction

What will happen when two waves meet? The purpose of this investigation is to work toward an answer to that question. You will need the slinky and the long, heavy coil spring you used in Investigation 32. Later, you will need the motorized ripple tank and Young's double-slit apparatus.

Exploration

1. Stretch the slinky coil out about eight meters along the floor as you did in Investigation 32. Practice making a few pulses until you can produce nice sharp ones and square ones. Make square pulses by quickly moving the end of the slinky to the side, hesitating momentarily, then quickly moving the end of the slinky back to the middle. Now, let your partner practice for a while. The trick is getting a good sharp pulse is to move your hand sideways as quickly as possible and then move it back to its original position as quickly as possible. When you and your partner are both able to send sharp, easily seen pulses, you are ready to begin the investigation.

2. Pulses meeting on the same side of the slinky. Generate a sharp pulse, and, at the same time, have your partner send one toward you on the same side from the other end of the slinky. Send sharp pulses toward square pulses, as well. Do the pulses cross each other or do they reflect?

   ____

3. How do pulses behave as they meet? Send a pulse toward your partner as he sends one the same size toward you on the same side of the slinky. Pulses about two feet in amplitude are convenient. Have the third member of your team mark the amplitude of the individual pulses on the floor when they have reached the middle of the spring and the amplitude of the combined pulse.

   a. How large is the amplitude of the individual pulse?

   ____

b. How large is the amplitude as the pulses meet each other?

____

4. On Figure 1, draw a picture of the pulses as they meet each other.

5. How did the amplitude of the spring at the point the pulses meet compare with the height of each individual pulse?

____

6. Try other combinations of pulse amplitudes such as a one foot pulse meeting a two foot pulse, etc. What can you say about how the amplitude of the pulse at the meeting point compares with the amplitude of the individual pulses just before they meet?

____

____

7. Now send a pulse toward your partner as he sends one toward you on the opposite side of the slinky from your pulse. Again keep the pulses the same size.

8. Look carefully as the pulses cross and draw what you see on Figure 2. What is the amplitude at the center when the waves meet?

____

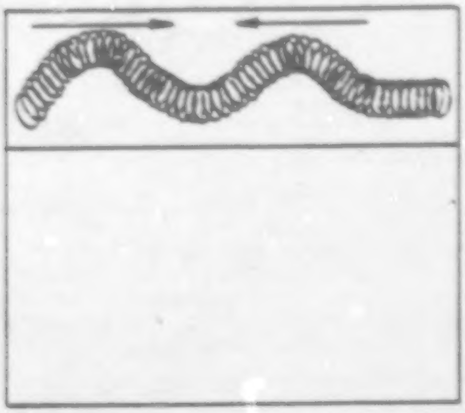

Figure 1

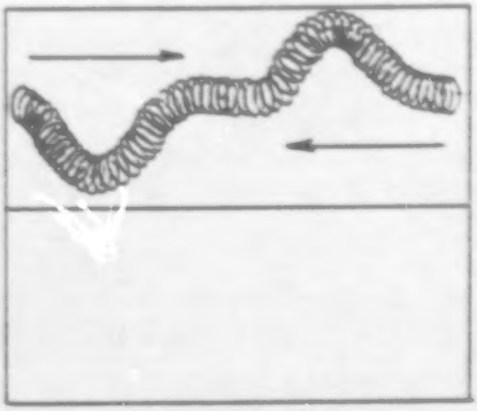

Figure 2

The Idea

9. Write down a general rule that will describe the behavior of pulses as they meet. (How can you determine what the amplitude of the combined wave will be?)

Now join the rest of the class for a discussion of the data you have gathered.

Expansion of the Idea

Part 1: An Experiment with Continuous Waves

Stretch the long, heavy coil spring to about four meters, just until it no longer touches the floor while you are in a standing position. Keep the spring off the floor throughout this part of the investigation. Now start putting one wave after another into the spring; your partner should hold the other end still. Waves that occur continuously have the following pattern .

10. Adjust the rate (frequency) at which you move the end of the spring from side to side until the spring appears to have sections that go from side to side and sections that just stand still. How does the greatest distance the spring is moving from side to side compare with the distance your hand is moving from side to side?

11. Draw a picture of what you see happening to the spring. Use the space below.

you ' - - - - - - - - - - - - - - - - - - ' your partner

12. How can you explain the observation that some points on the spring have greater amplitude than the waves you are generating?

13. How can you explain the observation that there are points of practically no vibration at all?

14. Look again at your drawing. How many complete waves are shown? (Remember a complete wave has a crest and a trough).

Name_______________________

Section____ _______________

Part 2: Problems

15. Suppose the following two waves were to occupy the same section of spring at the same time.

    a. According to the superposition principle, how would that section of spring appear at that time? Make the drawing on Figure 3.

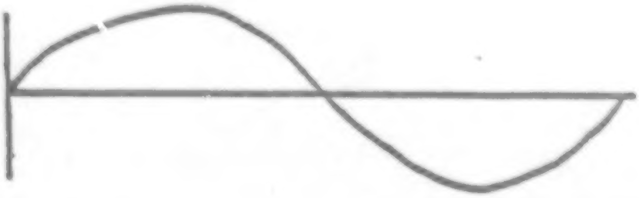

Figure 1

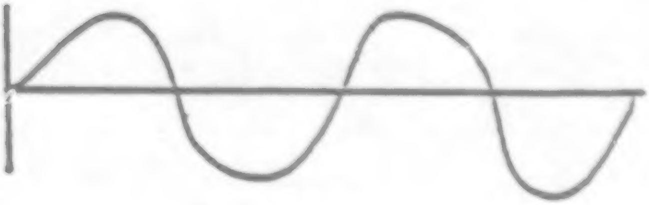

Figure 2

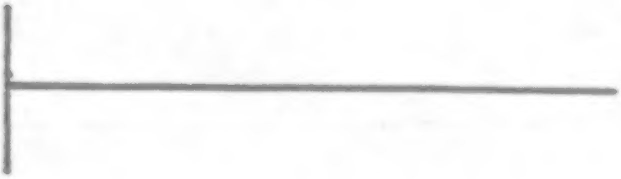

Figure 3

b. On Figure 3, above, mark and label sections of constructive and destructive interference.

16. How does the frequency of vibration of a small object floating in water compare with the number of waves passing it each second?

17. On the following page, combine the two waves according to the superposition principle. Study the wave pattern produced.

a. How would you describe the wave pattern?

____

b. If the waves represent sound waves in air and loudness is proportional to amplitude, how would you describe the sound produced by the two waves being superimposed on one another?

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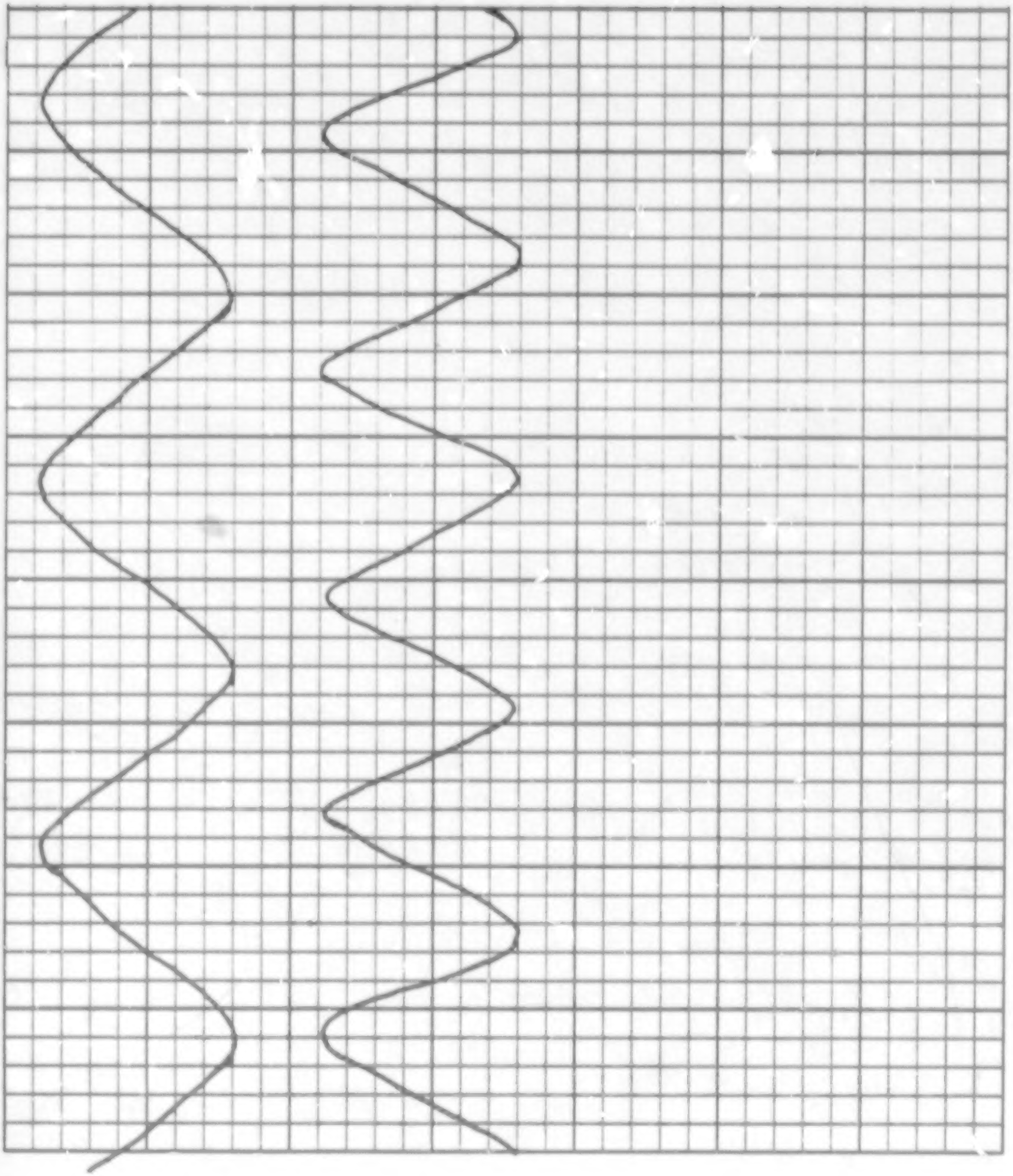

Expansion of the Idea

Part 3: Surface Wave Interference

Set up the ripple tank again as you did in Investigation 31 using the straight-edged metal or wood strip to make straight waves. Generate waves of about one inch wavelength. Then place a long, straight barrier into the tank parallel to the wave fronts. Move the barrier back and forth until you see lines that alternate from dark to bright and remain in one place.

18. Measure the distance between the lines you are observing.

____

19. How does the distance between the lines compare with the wavelength of the waves producing them.

____

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20. How can you explain the production of the series of alternating lines.

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Now replace the straight-edged strip attached to the motorized vibrator with two small round objects that come with the ripple tank and fit onto the vibrator. These objects are called point sources.

21. Let one of the point sources touch the water surface and then vibrate. Adjust the point source until the waves produced make the brightest, clearest image on the paper below the ripple tank. What kind of wave pattern is produced by a vibrating point source?

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____

22. Make a drawing of what you see in the space below.

Expansion of the Idea

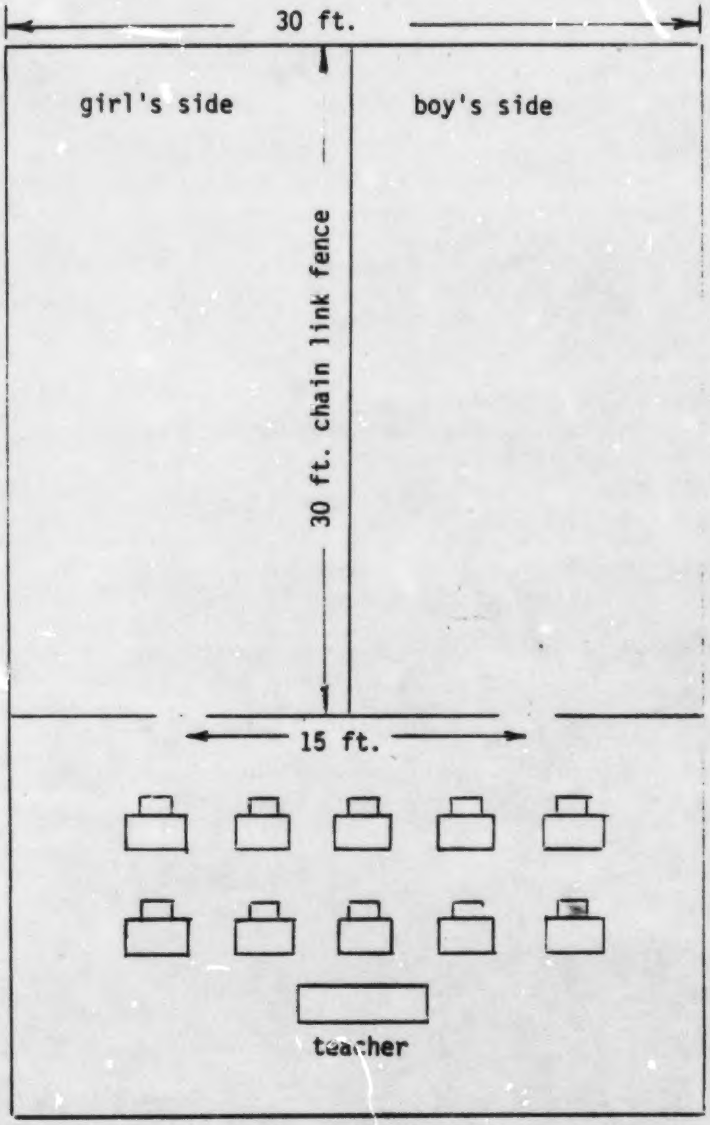
Part 4: Sound Wave Interference Problems

At a little country schoolhouse, the teacher uses a whistle to call the children to class. The whistle makes a sound wave that has a three foot wavelength. There are two small doors placed fifteen feet apart in the classroom.

This morning, during recess, Johnny was standing by himself at the back fence on the boy's side looking outward when the teacher, standing behind her desk, blew the whistle for school to start. All the boys and girls came in except Johnny. The teacher walked outside the door and blew the whistle again, at which time, Johnny turned and ran into the schoolroom.

The teacher angrily scolded Johnny for not coming in at the first whistle, but Johnny insisted he only heard one whistle. The teacher said this was impossible because all the other children heard the first whistle and came in immediately. Furthermore, when the teacher stepped outside and blew the whistle again, Johnny came in. So Johnny is now in trouble for failing to come in at the first whistle and for lying by saying that he heard only one whistle.

Johnny needs help from someone who knows physics. He appeals to you to explain to his teacher how he could have heard only one whistle. Your task is to explain how that could happen and where Johnny could have been standing.


30 ft.
girl's side
boy's side
30 ft. chain link fence
15 ft.
teacher

Scale: 1 cm represents 3 ft.

Figure 4

580

INVESTIGATION 33: MEETING WAVES STUDENT GUIDE

Name________________________

Section______________________

Expansion of the Idea

Part 5: Reading Questions

How did the Michelson-Morley Experiment destroy the old wave model for light?

INVESTIGATION 33: MEETING WAVES

READING: A WAVELENGTH FOR LIGHT

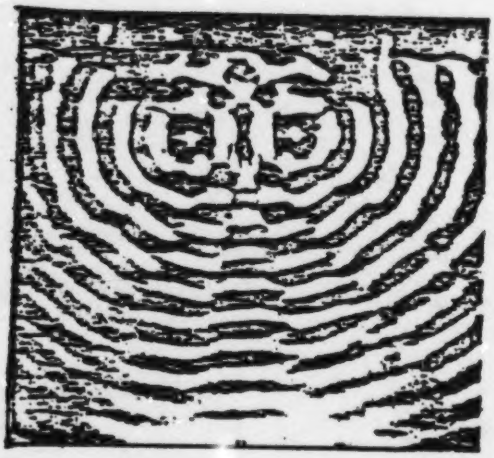


Figure 1

The photograph in Figure 1 shows a surface wave interference pattern like the patterns you observed with water in your ripple tank. Notice that you can see the nodal and antinodal lines in the pattern.

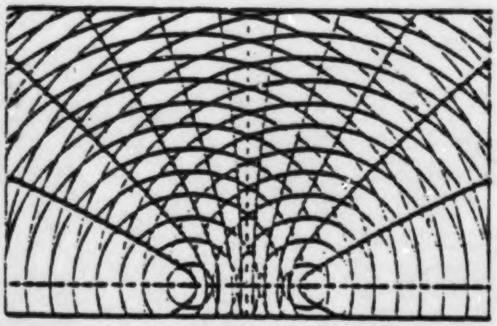


Figure 2

In Figure 2, you can see waves depicted by circular lines (the lines represent crests and the space between the lines represent troughs.) The bolder lines have been superimposed to show the lines of destructive interference (nodal lines) where trough;s and crests meet. Notice that crests meet crests between the nodal lines.

The reason you get the pattern shown in Figure 1 is that the nodal lines are areas of flat water and the antinodal lines are areas of bright and then dark (reinforced crests and reinforced troughs).

INVESTIGATION 33: MEETING WAVES

It is quite interesting and informative to look for some of the mathematical relationships that exist in the interference pattern. Suppose we choose a point P on the first nodal line to the right of the central antinodal line (the dotted line). We will call the point sources that make the waves S_l (for the left source) and S_r (for the right source).

In Figure 3, count the number of waves from S_l to P and record the number on a piece of paper. Also record the number of waves from S_r to P. Since each wave has a certain length (the wavelength), then the distance between S_l and P could be described as the number of waves between S_l and P multiplied by the wavelength.

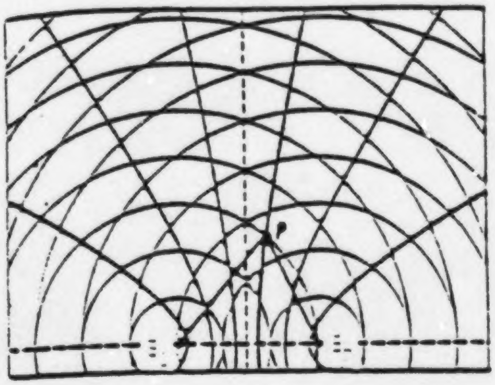


Figure 3

The same is true for the distance from S_r to P. Compare the difference in length between PS_l and PS_r.

Now choose another point, P_2, where the same nodal line crosses a crest. Again determine the distances P_2S_l and P_2S_r as multiples of the wavelength. Again find the difference in length. Do you again find that difference is $1/2\lambda$? We can say, then, that for any point P along the first nodal line $PS_l - PS_r = 1/2\ \lambda$.

If you use the second nodal line to the right of the central antinodal line, you find that $PS_l - PS_r = 3/2$. On the third nodal line, the difference is $5/2$. Do you see the pattern? If n refers to the number of the nodal line numbered from the central antinodal line, then the difference between some PS_l and PS_r will always be $(n-1/2)$. We could say that mathematically as follows: $PS_l - PS_r = (n-1/2)$.

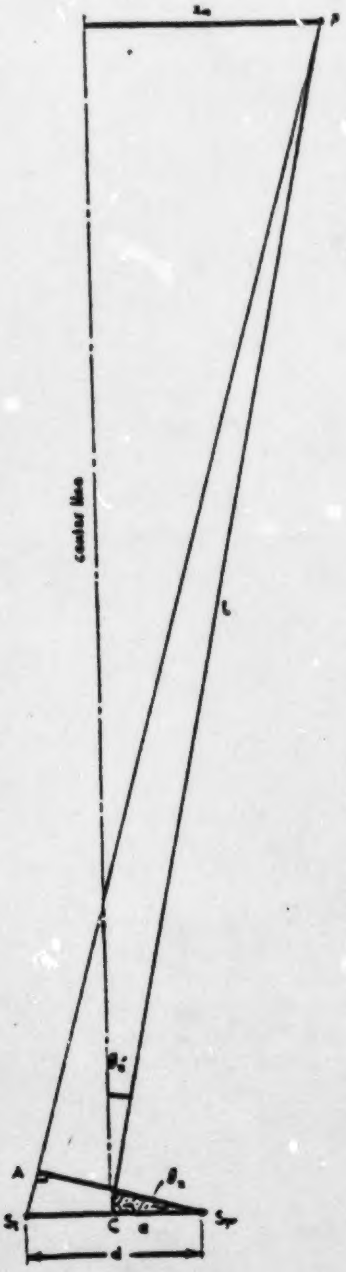


Figure 4

It is not the purpose of this reading to go into great detail about the mathematical relationships that can be found in interference patterns, so we shall try to move quickly through this section into the point of the reading. Before we do that, however, study Figure 4. You will notice that the interference patterns have been removed. The point sources S_1 and S_r are shown as well as the point P (a point on a nodal line). It can be shown that $\lambda = d(x/L)/n-1/2$. The point of this discussion is that if you can measure the distances d, x, and L, and if you know which nodal line (n) you are concentrating on, you can determine the wavelength of the wave producing the interference pattern.

Now look at Figure 5. You see a series of dark and light lines. Those lines have been produced with Young's double slit equipment, in other words, they have been produced by light interference.

The dark lines are nodal lines and the light lines are antinodal lines. The central light line is the central antinodal line we talked about earlier with water waves. If you set a ruler near your light source and measure the distance (x) from the center

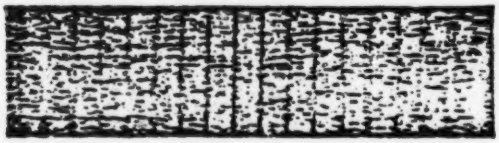


Figure 5

of the central antinodal line to the (nth) nodal line of your choice, and the distance from the ruler to the coated slide, then you should be able to determine the wavelength of the light (after you measure d, the distance between the slits).

The point is that the wavelength of light is measurable. Thomas Young first published this result of his research with interference of light in 1802. The result was the clear affirmation by scientists that light has wave properties. If light has a measurable wavelength, then light must be a wave. A second result was a growing confidence by scientists at that time in the ether model as the medium for light. Those who questioned the ether model were simply not heard.

By the way, the wavelength for visible light turned out to be around 10^{-5} cm.

INVESTIGATION 33: MEETING WAVES

THE MICHELSON-MORLEY EXPERIMENT

By the late 1800's, so much data had been collected revealing wave properties for light that the ether model seemed virtually certain of substantiation. It had been known since the time of Roemer that light has a measurable speed. Francesco Maria Grimaldi, professor of mathematics at Bologna, had shown that light diffracts (his work was published in 1665, two years after his death). Thomas Young had shown in 1802 that light displays the wave phenomenon of interference. In 1815, Augustin Fresnel (a young French engineer) was investigating the polarization of light and Thomas Young, in 1817, suggested on the basis of Fresnel's work that light waves are transverse, not longitudinal. In 1873, Maxwell published his Treatise on Electricity and Magnetism in which, building primarily on Faraday's investigations, he laid out his predictions made from mathematical statements about electricity and magnetism. Those statements suggested to Maxwell that electromagnetic radiations have the same speed as light, that electromagnetic radiations can be made to reflect and refract like light, and that light is an electromagnetic radiation. The obvious conclusion of all this work was that the ether is the medium for light, despite its absurdities (more rigid than steel yet unobservable).

In 1881, a young Ensign in the United States Navy expressed his interest in the quest for a precise determination of the speed of light and in the search for direct data supporting the luminiferous ether. The problem that occupied Albert Michelson (the young Ensign) was how to measure the effect of the ether on the speed of light. He took the problem seriously, thinking about it continuously, even laying awake at night.

It seemed to Michelson that light waves traveling in the ether should behave like a swimmer in a stream. It would take more time to go downstream and back up again than to go across and back even if the same distance were being traveled.

Let's consider this in more detail. Suppose a swimmer can swim at a speed of five feet per second in still water. Now suppose he wishes to swim downstream 100 feet and return. The stream flows at three feet per second. His speed downstream will be eight feet per second (5 ft/sec+3 ft/sec). From t=d/v, we can find his time to swim downstream: 100 feet/8 feet per second=12.5 seconds. His speed upstream then is 100 feet/2 feet/sec=50 seconds. His total time to swim downstream and back will be 50 seconds+12.5 seconds=62.5 seconds.

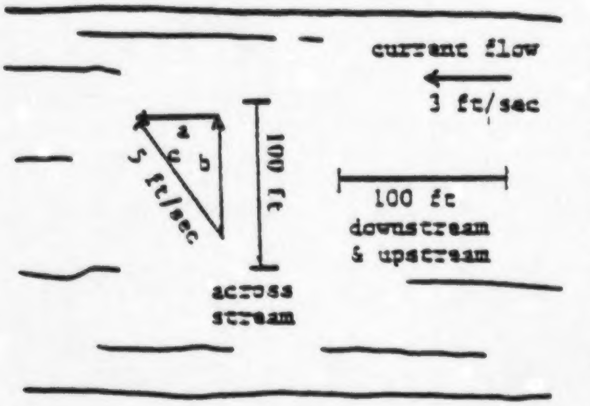


Figure 6

Now suppose that instead of swimming with or against the stream, our swimmer chooses to swim across the stream and back, 100 feet each way. To solve this problem, we must resolve a triangle of vectors because although he can swim five feet per second in still water, the current is carrying him downstream. Therefore, his actual speed across the stream is less than five feet per second. We know that in such a triangle, the law of mathematics $a^2+b^2=c^2$ applies, where a, b, and c are sides of the triangle, and c is the hypotenuse. Side b (which represents the actual speed of the swimmmer across the river) is given by $b^2=c^2-a^2$. Substituting values for the variables: $5^2-3^2=25-9=16=b^2$. Therefore, b=4 feet per second. So the swimmer can cross the river at 4 feet per second. His time for such a trip would be t=d/v=100 ft/4 ft/sec=25 seconds. Since the river will have the same effect on him during his return trip, his return time will be the same. Therefore, his time to cross the river and return will be 25 seconds+25 seconds=50 seconds.

Now compare the time it takes the swimmer to go downstream and back with the time it takes him to go across the river and back. His downstream-and-back time is 62.5 seconds. His across-and-back time is 50 seconds.

Michelson figured that since the earth is moving through the ether, the ether is flowing imperceptibly by, somewhat like water in a stream. Therefore, it should take more time for light to go a certain distance downstream and back than to go across and back. If he could measure the effect of the ether wind on the speed of light, he could prove that the ether existed. Thinking about and finding a way to prove it were two different things, but in the end he used the concept of interference and some ideas for equipment from Armand Hippolyte Fizeau, a French physicist, who had done some work on measuring the speed of light.

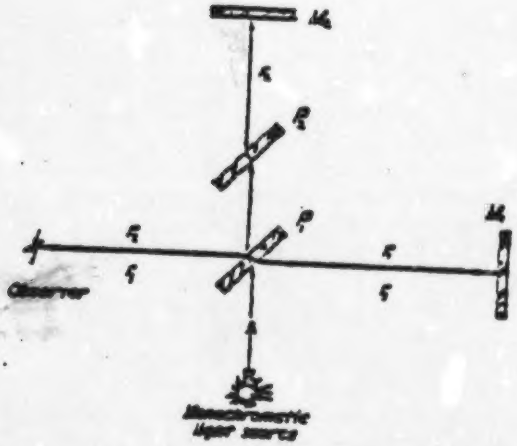


Figure 7

Figure 7 shows the basic equipment Michelson used to make the interferometer (interference meter). The light source is monochromatic (one color). The glass plate, P_1, is covered on the back surface with a layer of silver so thin that some of the light is reflected and some is refracted. The glass plate, P_2, is cut from the same piece of glass as P_1, so that it has the same optical properties. Mirror M_1 is fixed in place at right angle to mirror M_2, however M_2 is equipped with an adjustable screw so that it can be moved back and forth about the distance of a wavelength of light.

The equipment, therefore, provides light the opportunity to be reflected at P_1, reflected at M_1 refracted at P_1 to the telescope of the observer. Or the light may be refracted at P_1, refracted at P_2, reflected at M_2, refracted at P_2 and reflected at P_1 to the telescope. The point of using the semi-reflecting mirror at P_1 is that some light will take each route.

INVESTIGATION 33: MEETING WAVES

Notice that no matter which way the light goes, it will travel the same distance and undergo the same number of refractions and reflections. Therefore, if there was no ether wind, light should go both routes and return to P_1 (and to the telescope) at the same time. Crest should meet crest, trough should meet trough. There should be no destructive interference. If there is an ether wind, light should take longer to go downstream and back than to go across and back. Crests that were together at P_1 should return to P_1 at separate times and interfere with each other. The same is true for troughs.

Michelson set up his equipment at the University of Berlin in the laboratory of Hermann von Helmholtz (the physicist who had shown mathematically that the law of conservation of energy is valid) on a solid stone pier. There were, however, problems, such as the vibrations due to the Berlin traffic. He had the equipment transferred to the Astrophysical Observatory at Potsdam where he set it up below a large telescope. The instrument was so sensitive that it even registered the vibrations due to footsteps a block away.

When Michelson looked through the scope, he could see the image of mirror M_2 superimposed on M_1. He could adjust M_2 so that he could see interference bands in the scope. He could also adjust M_2 so that no interference bands were visible. If he would then rotate the table (on which the equipment was fastened) he should see shifts in the interference bands as the light changed directions through the ether.

When Michelson performed the experiment, he saw none of the expected shifts.

What could have gone wrong? Could the equipment have failed? Could it be that the pre-Copernican natural philosophers had been right and the earth does not move through the ether? Or could it be that the earth drags some ether with it so ether measured near the surface would be stationary? When Michelson wrote his observations and published them in the August, 1881 issue of the American Journal of Science with the title "The Relative Motion of the Earth and the Luminiferous Ether," he stated his conclusions very simply, "The hypothesis of a stationary ether is erroneous."

INVESTIGATION 33: MEETING WAVES

In 1882, Michelson met Edward W. Morley. They traveled together a good deal and were interested in the same subjects, namely the speed and medium of light. By 1885 they were working together and submitted a paper for publication in the American Journal of Science in 1886 dealing with the influence of the motion of the medium on the velocity of light. Then their attention turned again to the problem of using the interferometer to measure the effect of the ether on the speed of light. Michelson's first paper had created a flurry of argument among scientists around the world; there certainly was not total agreement on the results of that work.

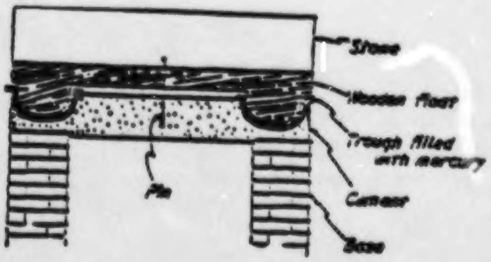

Stone
Wooden float
Trough filled with mercury
Pin
Cement
Base

Figure 8

They set up their equipment in Cleveland, Ohio. The equipment consisted of a large five foot square stone slab, fourteen inches thick which rested on a wooden float with a donut shaped bottom which floated in a donut shaped trough filled with mercury.

This construction allowed the slab to be rotated while remaining constantly level. Michelson added more mirrors to the interferometer so that the light path was greatly increased in length, therefore increasing also the precision of the apparatus.

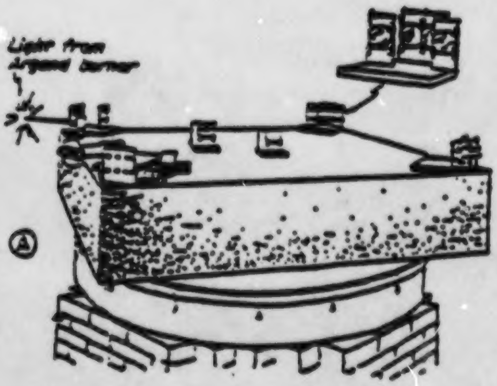

Light from Argand burner
Ⓐ

Figure 9

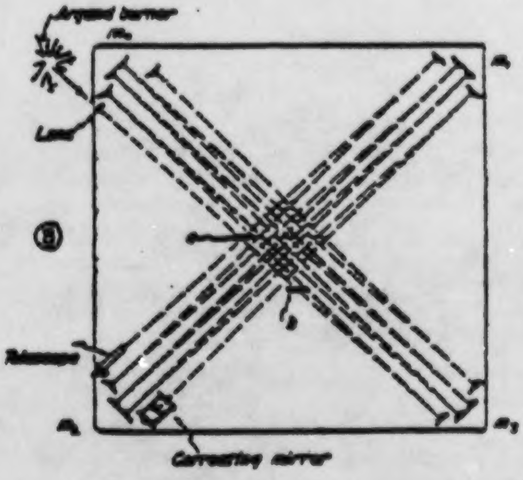

Argand burner
Lens
Ⓑ
Telescope
Correcting mirror

Figure 10

Table I

	Distance Between Adjacent Nodes	λ ( )	f ( )	v ( )
1				
2				
3				
4				
5				
6				

The Idea

4. What is the relationship among the velocity values in Table I?

5. What relationship appears to exist among λ, f, and v?

6. How does λ change as f is increased?

INVESTIGATION 34: PERIODIC WAVE RELATIONSHIPS STUDENT GUIDE

Name________________________

Section______________________

Expansion of the Idea

Part 1: The Tiny Surfer

Imagine that some physics students were investigating the physics of waves using ripple tanks in a land of tiny people. The physics students learned to know the tiny people and as a favor let them use their ripple tanks for surfing. It occurred to the physics students that they could use a surfer and the relationship $v = \lambda f$ to determine information about the waves in the ripple tank.

The following is a picture of a surfer in the tank. Assume the picture is actual size and the surfer moved the distance shown in 1.0 second.

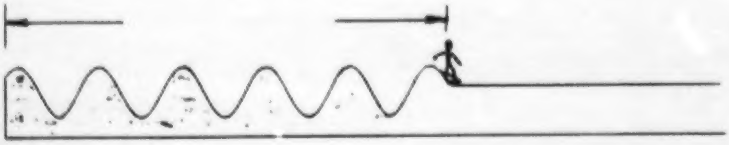


Figure 1

7. Based on the information above, determine the frequency of the waves.

8. Determine the speed of the waves in the ripple tank.

9. Determine the wavelength of the waves in the ripple tank.

Name________________________

Section_______________________

Expansion of the Idea

Part 2: Problems

1. How does the frequency of vibration of a small object floating in water compare with the number of waves passing it each second?
2. A duck in a lake bobs up and down completing 9.0 cycles in ten seconds. One crest moves from the duck to the shore, 9.0 meters away in 5.0 seconds.
   a. What is the frequency of the wave?

   b. What is the speed of the wave?

   c. What is the wavelength?
3. From an airplane, swells (crests) of waves in the ocean are estimated to be 200 meters apart. It is found that a swell passes a given point every ten seconds.
   a. What is the wavelength of these waves?

   b. What is the period of a wave?

   c. What is the frequency of the waves?

   d. What is the speed of the waves?

4. Standing waves can be produced on a string by tying it to a household current vibrator which then vibrates at 60 cycles/sec. If the other end is attached tightly one meter from the vibrator and the resulting standing wave has the following appearance, find the velocity of the waves in the string.

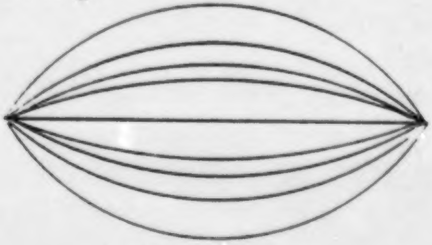


Figure 2

5. In a ripple tank the wavelength of waves in deep water is 3 cm. When they pass into shallow water their wavelength decreases to 1 cm.

   a. Compare the velocities of the waves in the two media.

   b. If the motor is producing the waves at a frequency of 3 cycles/second, find the velocities of the waves in the two media.

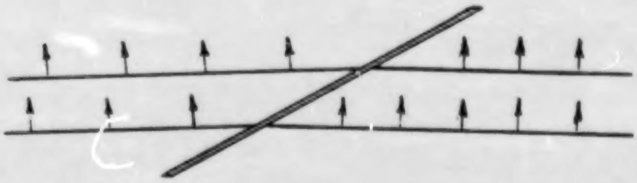


Figure 3

6. In the drawing of refraction above, assume the velocity of the waves in the deep water (medium 2) to be 7.7 cm/sec. In the shallow water (medium 1) v=5.2 cm/sec. The wavelengths are 1.48 cm in medium 2 compared with 1.0 cm in medium 1.

   a. find the frequency of the waves in medium 1.

   b. find the frequency of the waves in medium 2.

   c. How do the frequencies of the waves in the two media compare?

   d. Write an equation which, in general, will relate v_1, v_2, λ_1, and λ_2 when the wave is refracted from medium 1 into medium 2.

INVESTIGATION 34: PERIODIC WAVE RELATIONSHIPS STUDENT GUIDE

Name________________________

Section_____________________

Expansion of the Idea

Part 4: Reading Questions

Astrophysists make use of phenomena called the blue hift and the red shift. When a light source approaches the earth, the frequency of the light associated with it increases. When the source recedes, the frequency of the light decreases. Why would blue shift and red shift be appropriate descriptions of these events?

INVESTIGATION 34: PERIODIC WAVE RELATIONSHIPS

READING: COLORS

The telescope had been invented by Hans Lippershey in Holland in 1608. People had experimented with lenses before that time, but that particular combination of lenses was unique. When Galileo heard about the invention, he stayed up all night trying to figure out how Lippershey must have constructed it and in the morning he started making one. Apparently, it was Galileo who first thought about looking at the stars with a telescope. Others had preferred to look at more terrestrial objects, primarily people, which is why it was originally named spy glass.

Therefore, by the time of Isaac Newton, telescopes were popular instruments. A pesky problem interfered with the use of telescopes, however, in the form of a colored border that always surrounded the image formed by the main lens.

That colored border had been seen and ignored by many people. Newton shows us the difference between a casual and a true observer--the urge to investigate. Newton was bothered by the border and decided to investigate its cause. It is often those ignored little problems that would change our perspective, if we invested the time to study them.

Newton had a triangular glass prism made for him and let a beam of sunlight pass through a small hole in his window shuts. He placed the prism at the place where the beam entered his room so that the light would be refracted on the opposite wall. The result was the production of rainbow colors, each color an elongated circle.

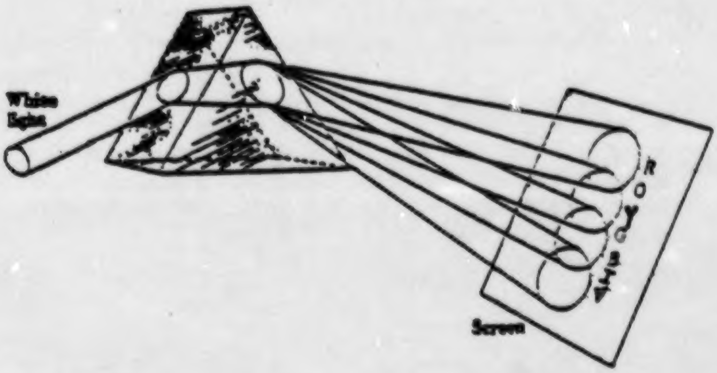


Figure 1

For a while, Newton just played with the equipment much like anyone would, finding the colors a "pleasing divertissement". Later he began to ask some serious questions about the source of the colors. Where do they come from? Why is the image oblong rather than circular like the hole? He tried a number of changes--different thickness of glass, different sized holes in the window; he even tried putting the prism outside the window--but none of the changes gave him answers to his questions.

One problem he wanted to solve concerned the source of the colors. It had occurred to him that either the prism could make the colors, or the prism could just separate the colors that were already in white light. To find out, he passed the colored rays produced by one prism through a second prism in the reverse direction. The result was the production of white light by the second prism.

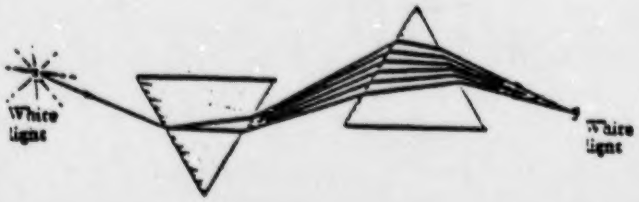


Figure 2

This convinced Newton of something he had already suspected, but hadn't known for sure, the colors were already in the white light that came into his room through the hole in the window. The prism merely separated them.

The fact that the colors were separated when he made white light pass through the prism, Newton interpreted to mean that the glass had an index of refraction slightly different for each color. Newton had worked with Snell's Law, but Snell's Law had always been used in the context of white light. Now Newton saw that it applied to the colors also.

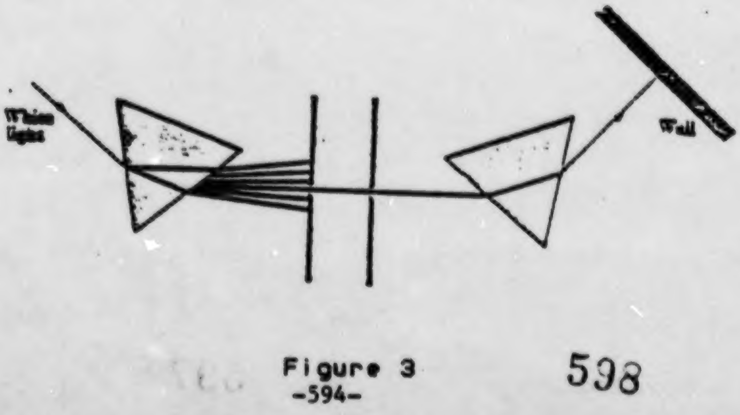


Figure 3

INVESTIGATION 34: PERIODIC WAVE RELATIONSHIPS

Newton arranged a system of two slits and a second prism to find out whether the colors could be refracted into still more colors. He discovered that they could not. Careful measurements of the wavelength of each color shows that the colors are not single wavelengths so many centimeters/cycle apart, but rather are ranges of wavelengths with color being the interpretation of the human brain. Therefore, the spectrum (Newton's word for the colored pattern) is called continuous because light of every wavelength within the range is interpreted by the brain as having that color. Below is a table of the colors and the range of wavelengths associated with each color.

Wavelength Range ($\times 10^{-5}$ cm)	Color
7.5 to 6.1	Red
6.1 to 5.9	Orange
5.9 to 5.7	Yellow
5.7 to 5.0	Green
5.0 to 4.5	Blue
4.5 to 3.8	Violet

Notice that each value must be multiplied by 10^{-5} cm, which means that the wavelengths for light are very small compared with distance measurements that we commonly make.

Further, since light is an electromagnetic radiation, and not the only electromagnetic radiation, we should see that the spectrum is not limited to visible light. In fact, it includes radiations of other frequencies (and wavelengths) which we cannot see. Below is a table of a more complete list of radiations in the spectrum.

Radiation	Wavelength Range (cm)
Electric waves	10^{12} to 10^{6}
Radio waves	10^{6} to 10^{-1}
Infrared rays	10^{-1} to 10^{-4}
Visible light	10^{-5}
Ultraviolet	10^{-5} to 10^{-6}
X-rays	10^{-10} to 10^{-9}
Gamma rays	10^{-10}
Cosmic rays	10^{-10} to 10^{-14}

INVESTIGATION 34: PERIODIC WAVE RELATIONSHIPS

(If you recall the reading, Other Waves, which you read earlier in this course, you may want to refer to it again for some of the uses of the various electromagnetic radiations.)

You may have wondered how the various radiations are related in terms of the energy they carry. You are not the first. If you recall your work with slinkies and water waves, you found that the energy in the wave is related to the amplitude of the wave. However, if you fix the amplitude, you can vary the energy carried by waves by varing the frequency. The higher the frequency, the greater the energy in the wave. On December 14, 1900, Max Planck announced ideas which gave birth to the quantum theory. Among those ideas was a relationship which showed that the energy in electromagnetic waves is dependent on the frequency of the wave. Therefore, looking again at the electromagnetic spectrum and applying $v = \lambda f$, you can see that the energy in waves increases as the wavelength decreases. Therefore, those radiations higher in the chart have lower energies and those lower in the chart have higher energies. That also partially explains why ultraviolet, X-ray, and gamma ray exposures to the human body need to be controlled. They can do serious damage to body tissue. Cosmic rays generally are not available in large enough ammounts to pose a serious threat.

Name__________________________

Section________________________

Introduction

No matter how hard you blow over the top of a bottle, you can only get one or two notes out of it. Yet, the same bottle will produce many different pitches if you fill it to different levels with water. Some small radios seem to buzz when the radio plays a certain note and well-trained singers can break crystal with their voices. In this investigation, we will try to build an understanding of these events. We will assume that sound is a wave phenomenon and use wave concepts to study sound.

Exploration

The instructions that follow are based on a glass tube and cylinder as your equipment. If you have a resonance apparatus, ask your teacher how to modify the procedures.

1. Fill the large cylinder nearly full of water. Lower the glass tube into the cylinder until the top of the tube is barely above the water.

2. Have your partner strike one of the tuning forks on a soft surface (the heel of the hand or on a rubber stopper held in the hand is fine). DO NOT strike the tuning fork on a hard surface (tabletop, shoe, head, etc.). While the tuning fork is vibrating (humming), your partner should hold it over the top of the tube, just above the surface of the water.

3. Lift the tube (and the tuning fork) slowly until the sound of the tuning fork is magnified. Measure the length of the tube at this point and record it in Table I. Also record the frequency of the tuning fork.

4. Repeat steps two and three with two other tuning forks of different frequencies.

Table I

Tuning Fork	Frequency	Length of Air Column in Tube (m)		
1				
2				
3				

5. Measure the inside diameter of the tube you used and write it here.

d=____

INVESTIGATION 35: SOUND

STUDENT GUIDE

Name________________________

Section________________________

The Idea

When you strike a tuning fork and hold it in the air in front of you, you will hear a sound of a certain intensity or loudness. If you strike the tuning fork more vigorously, you see the tines of the tuning fork are vibrating with a greater amplitude and the sound reaching your ears is louder. From this information, it would seem reasonable to assume that the amplitude of a sound wave is somehow positively related to the loudness of the sound you hear. That is, when the amplitude of a sound wave increases, you will hear the sound as increasing in loudness.

1. You know that waves carry energy (or are a form of energy) and you have been told that sound is one type of wave. In this investigation, when you hear a sound, from where does that energy come?

2. When you lift the tube and the sound level increases, more energy in the form of sound waves reaches your ears. From where does the extra sound appear to be coming?

3. Is the sound from the tube the same as from the tuning fork? How does the frequency of the sound coming from the tube compare to the frequency generated by the tuning fork?

4. Although the resonating tube appears to be radiating sound, it can be shown that it is not losing chemical or potential energy. The tube is not moving, either, so it has no kinetic energy to lose. What would the Law of Conservation of energy lead you to conclude about the hypothesis that the resonance tube is generating (creating) sound?

5. You studied wave interference in Investigation 33. Which type of interference increases the amplitude of a wave at a certain point without requiring that energy be added to the wave?

____

6. Use the space below to tell why it would (or would not) be possible for this type of interference to explain the resonance you found in this investigation.

7. What point on a standing wave has the greatest amplitude?

____

8. What part of a standing wave would you put at the top of the tube to reproduce the resonance you found?

____

a. Why?

____

____

____

b. Is the end of the air column at the water surface a node or an antinode of the standing wave you have described? Why?

c. Use the diagram below to draw possible standing wave patterns in the air column.

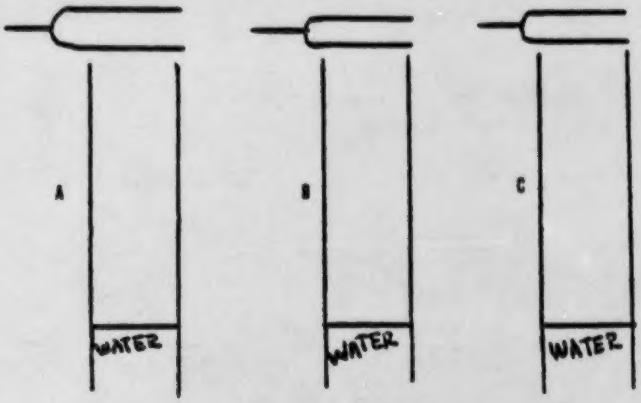


Figure 1

9. Look back at your laboratory procedure. In terms of what you did, which of those standing wave patterns did you most likely establish in your investigation? (Your answer should be given in terms of the number of wavelengths.)

10. The fourth column of Table I is for the wavelength of each tuning fork. Fill in that column now, based upon your answer to the previous question.

11. Since sound is a wave phenomenon and shows the properties of waves, it should follow wave relationships. Using the wavelength and frequencies in the table, calculate the speed of the sound waves for each of the frequencies you used. Enter these values in the fifth column of Table I. Are these values variable or constant?

Name________________________

Section_____________________

Expansion of the Idea

Part 1: Problems

1. An oscilloscope is a kind of television tube which can be used to change a sound wave to a visible wave pattern on the screen. Assume that the wave pattern shown below is a sound wave pictured on an oscilloscope screen. Draw a pattern in the empty box that would represent a sound of twice the frequency and half the intensity (amplitude) of the one pictured.

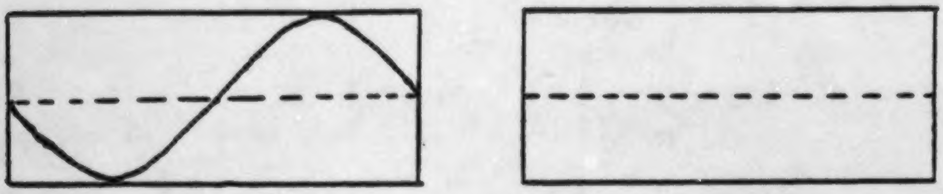


Figure 2

2. A car is facing a stone canyon wall. The driver produces a short beep on the horn and hears the reflected wave (echo) five seconds later. How far is the car from the wall?

3. The untrained ear cannot distinguish two sounds as separate unless they are more than 0.1 seconds apart; otherwise, the sounds blend into a single sound. What is the closest one can be to a sound reflecting wall and still hear an echo?

4. Concert pitch for many orchestras is 440 Hz (A above middle C). What is the wavelength of this sound wave in air? (Assume the speed of sound is 340 m/sec.)

5. How does the speed of high-pitched sounds compare with the speed of low-pitched sounds?

6. Explain why your voice seems louder in a house than outside even though your are not talking louder.

7. Why does sound not travel through a vacuum (science-fiction movies notwithstanding?)

Expansion of the Idea

Part 2: Reading Questions

1. How could you tell which pipes of a pipe organ produce the low pitches and which produce the high pitches without getting close enough to the pipes to tell from which direction the sound was coming?

2. Using the idea of resonance, explain why apartment dwellers often complain that they can hear the low notes from their neighbors' stero sets, when they do not hear the high notes at all.

3. Which of the two bandshells (sound reflecting surfaces in the drawings below) would have better acoustical properties? Be sure to explain and defend your answer thoroughly. Sound ray diagrams may be helpful in your explanation.

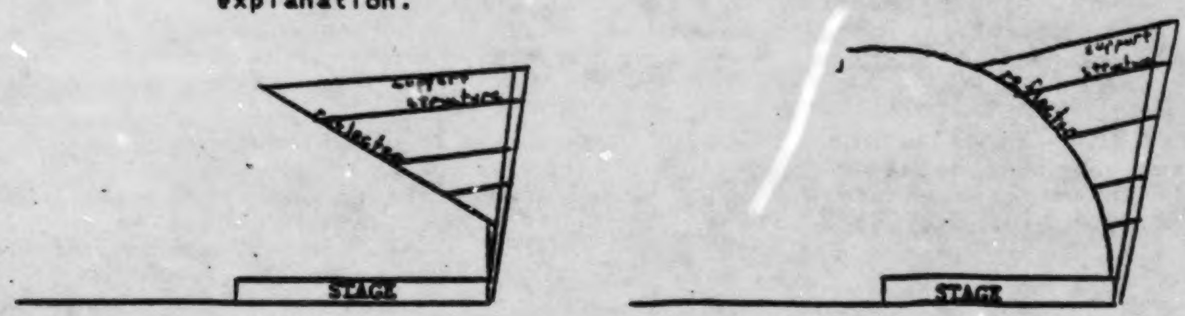


Figure 3

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READING: ORGANIC MUSIC

The physics of resonance explains many things that did not appear unusual, when you did not know what resonance was. Many of these things had been taken for granted until resonance became explainable and are now the subject of complex study. The real-life applications of resonance are a constant good news/bad news story and we will explore some examples of each here.

Perhaps the most straightforward example of resonance as a useful phenomenon is the pipe organ. The sound of a pipe organ is generated by an air column vibrating in each of several pipes (is this the beginning to sound familiar?). Each pipe in a pipe organ is capable of resonating only one frequency (pitch), and so each time a pipe organ produces more than one note, you can be sure that more than one of the organ's pipes is resonating. Organ manufacturers have found that it is advantageous for them to construct pipes three-fourths of the wavelength of the sound to be resonated, so the second antinode of the standing wave is used to generate sound.

The lowest pitch produced by large pipe organs is a very low note of C that is felt rather than heard because its frequency is 16.35 Hertz, in the subsonic--below hearing--range. The highest note produced by very large pipe organs is a high C about two octaves above any other instrument, and has a frequency of 16,744 Hz.

Different types of sound quality (timbre) are often useful in music, and so many different types of pipes (of different materials and shapes, even though the lengths of the pipes are constant) may be available to be connected to one key. The mechanisms used for this are called stops, and it is possible to connect more than one of the pipes to a key at any one time, providing many possible combinations of sound quality.

The first organs date back more than 2,000 years. An engineer named Ctesibius designed an organ using water power in the second century B.C. The organ seen today is basically the same form as was developed in the 14th century A.D.

The majority of organs have two manuals (keyboards played with the hands) and one pedalboard (a set of pedals laid out as a keyboard that can be played with the feet). The organ of average size has about 500-1,000 pipes.

INVESTIGATION 35: SOUND

Among the largest organs ever built was installed in Convention Hall in Atlantic city, N.J. in 1932. It has 1,250 stops, and 32,882 individual pipes. The organist's console had seven manuals and one pedalboard. This large combination of stops and keyboards made it possible to change timbre quickly by changing from one keyboard to another, which had been present to have different sound qualities.

None of the sounds that are taken for granted from a pipe organ would be produced at all without resonance. Air from a compressor flows through a channel below the pipes of the organ, the stops of which are set to allow the air to enter some pipes and not others. When the key on the keyboard is depressed, the air in the channel is allowed into the key channel. In the key channel, the way the organ's stops are set determines which of the pipe openings (that correspond to that particular pitch) are open to let air pass through the pipes. When air enters the pipe, the tone to be resonated is usually produced in one of two ways. A flue pipe produces a tone much the same way that you do when you shape your mouth into an 'o' and whistle. A reed pipe produces sound by forcing air over a thin strip of material, which vibrates to produce the sound which is resonated by the pipe.

READING: HARMFUL RESONANCES AND SOUND REFLECTION

A bridge in Tacoma, Washington vibrates violently and even seems to hum for a few moments before it tears itself to pieces and collapses. A small pocket radio seems to rattle when it plays a certain note. An auditorium has a very annoying ring when a certain note is played onstage. What do these problems have in common? They are all examples of how resonance can be a destructive occurrence.

The wind does not make any sound as it blows through an open field or across the sky, but it is often heard to sigh when it passes through steel towers, trees, or howl if it finds a crack in a window or wall of a building. Every object has a frequency at which it vibrates best, known as its natural or resonant frequency. If sound energy is provided to the object at the object's resonant frequency, the object will resonate.

In the case of the Tacoma bridge, the wind at a certain speed and from a certain direction caused a sigh in the bridge structure that was the same frequency as the natural resonance frequency of many of the pieces of steel used to build the bridge. Bystanders reported that the bridge seemed to sing a note, then vibrate violently, and then the roadbed of the bridge flew apart. Resonance takes its toll.

Enrico Caruso (a famous operatic tenor of about 1900) had a parlor trick that made him very popular with partygoers, but not with hostesses. Good crystal glassware is made of very pure materials, and so has clear natural frequencies. Caruso would tap a wine glass lightly and listen to its ring. He would then hold the glass in front of his face and sing that note, increasing the intensity of his singing until the glass resonated sufficiently violently and broke. The type of glassware that works best for this demonstration is very expensive, which partially explains Caruso's unpopularity with party hostesses.

Auditoriums can have serious problems with acoustics (the sound reflecting and absorbing properties of a room) if they are not carefully designed and constgructed. The field that deals with sound quality in buildings is called architectural acoustics.

If a surface in an auditorium is perpendicular to a line drawn from the stage, the law of reflection indicates that the sound from the stage will be reflected back toward it. When a note is played from the stage so that the distance to the wall is some multiple of $1/4\ \lambda$, a standing wave can be set up that will allow the auditorium to become a giant resonator (see Figure 1). The longer the note is held, the greater the amplitude of the standing wave becomes (up to a point), and the more annoying the ringing sound becomes. Very few surfaces in good auditoriums are perpendicular to the stage, so that when reflection takes place, the waves are not reflected directly back to their source.

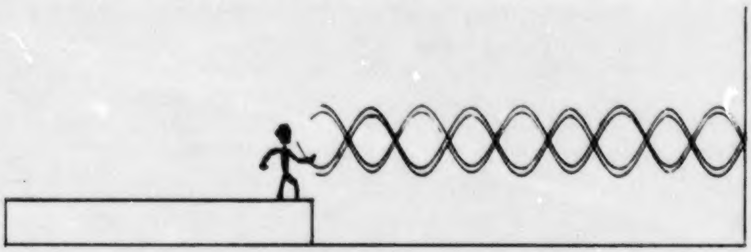

Figure 1

Different materials absorb different amounts of sound energy. While 100% of the sound energy striking an open window is absorbed by it, smooth marble absorbs only 1%, and reflects 99% of the sound energy that strikes it. Plaster and painted wood each absorb 3-4% of the sound energy, reflecting 96-97%. People absorb 10-20%, which is part of the reason that auditorium floors are sloped upward (so that every seat has a clear sound path from the stage). It also keeps the patrons happiest when they can see the stage.

In designing an auditorium, it is advantageous to make the audience area wider than the stage, so that a larger number of people can be seated close to the stage than is possible in a rectangular floor plan. Ceiling and sidewall reflections can be used to improve the sound levels at the rear of such a hall, but these reflections must be carefully controlled. If the stage-listener path is different from the stage-reflecting surface-listener sound path by more than twenty meters, the listener will hear an echo. Difference in the length of the sound path less than twenty meters will not result in an echo, but will cause the sound to be blurred. Care must also be taken to avoid making the rear wall of an auditorium into a concave sound reflector, or unfortunate focusing effects are likely to occur.

In one extreme case, the First Christian Church of Tomorrow in Oklahoma City has an egg-shaped dome ceiling. The church had such severe echoes that one parishioner reported that when the minister spoke, it sounded "as though God were repeating every word he said, only much louder." This problem was caused by a combination of floor-ceiling distance (being large enough to allow echoes) and a plaster ceiling that was a very efficient sound reflector.

In cases where reflections can be a problem, there are solutions short of rebuilding the entire structure. Surfaces which will reflect sound in a manner that will interfere with sound quality can be covered with sound absorbent materials, such as felt (58% absorption) or draperies (40-70% absorption). The source of the sound can also be changed. Several small, low volume speakers placed around the room can substitute for one large speaker system centrally located. This solution was used at the church described above.

INVESTIGATION 35: SOUND

Television coverage of football games makes good use of the focusing of sound by concave reflectors. Sideline microphones are often placed at the focal point of a lightweight parabolic reflector. A pointer (attached along the major axis of the paraboloid) is aimed at the players on the field and the signal-calling and crunching sounds picked up by the microphone add realism to the broadcast.

READING: JOHN QUINCY ADAMS--THE SNOOZING STRATEGIST

John Quincy Adams was the sixth president of the United States, but the reputation he carried in his day was due not to his acts as president, but to his skill as a legislator. When his attempt to be re-elected as president failed, he ran for the U.S. House of Representatives. He became known as Old Man Eloquent while in the U.S. House. He always seemed to know what the opposition party was going to do, even before they did it, which was very helpful in parliamentary maneuvering on the floor.

Adams's command of the political situation was a cause for bewilderment among the leaders of the other party, because the former president spent a large part of the time he was in the House chambers with his head down, apparently asleep at his desk! He seemed to wake up just often enough to instruct his party on the course events would take, and cast his own vote, following which, his head would sink back down to his chest. John Quincy Adams died of a stroke in the Capitol building in February, 1848, and the country lost an excellent leader.

In the middle of the 1800's there was a flurry of activity, and several new states were added to the Union in a relatively short amount of time. The Capitol building needed expansion, and rather than expand the existing chambers, the congress decided to add larger chambers on to the ends of the building, leaving the original House and Senate chambers for other uses. The workmen moving equipment noticed some curious things: the high, arched ceiling of the House chamber was very acoustically reflective and had a pair of hot spots. Facing the floor at one spot, the workmen could hear perfectly what was going on at the other spot, even if it was softly whispered. The entire ceiling of the chamber was found to be a good sound reflector, but reflections were particularly strong at these points.

So, if you ever take a tour of the U.S. Capitol building in Washington, D.C., the tourguide may point out the spot (marked by a small brass plate) in Statuary Hall where former president John Quincy Adams spent so much of his time. The tourguide may go across the hall to where the opposing party held their policy meetings and planning sessions. The tourguide may whisper towards the floor at this point. If he or she does, you will find that in the place where John Quincy Adams's desk sat, you can hear every word--even with your head down and your eyes closed, as if you are asleep!

Name________________________

Section______________________

Introduction

Why is it that some combinations of pitches are pleasing to the ear and other combinations of pitches are not? What is inherent in the relationships among frequencies that causes this to happen?

Exploration

1. Find two tuning forks that sound like the first two notes of the song Here Comes the Bride when sounded one after the other. Record the frequency of the lower pitch and the frequency of the higher pitch in Table I.
2. Find two more sets of tuning forks that show the same tone pattern (the first two notes of Here Comes the Bride) and record their respective frequencies in Table I.
3. Use the column of the table labeled ratio to enter the result of dividing the higher frequency by the lower frequency for each pair of tuning forks.
4. Repeat steps one through three, this time using the sound made by the C (256 or 261 Hz) and G (384 or 392 Hz) as the first tone pattern and entering your data in Table II.

Table I

Frequency		
Higher Pitch	Lower Pitch	Ratio

Table II

Frequency		
Higher Pitch	Lower Pitch	Ratio

The Idea

1. How do the ratios for the first interval you studied (called a fourth) compare with each other?

____

____

____

2. How do the ratios for the second interval (called a fifth) comoare with each other?

____

____

3. Put each of the ratios into its closest equivalent fraction (using integers).

Fourth______________________________

Fifth______________________________

Expansion of the Idea

Harmonics Problems

1. a. What is the frequency of a note one octave above C′, 522 Hz?

   b. How do the wavelengths of these two notes compare?

2. How will the pitch of a tuning fork change if you strike it with a harder blow?

3. Using your definition of harmony, explain why the notes E (330 Hz) and F (352.6 Hz) are not in harmony.

4. Compare the pitches of the following notes:

   a. the first note and another note an octave and a fifth higher

   b. 440 Hz and 330 Hz

   c. F (352 Hz) and A (440 Hz)

5. You are given a note A (220 Hz). Find the following frequencies:

   a. A fifth above the A

   b. A fourth above your answer to Part a

   c. An octave above the original note A

6. How do your answers to Question 5 (Parts b and c) compare? Give at least one example of how this information could be useful.

7. Just as an oscilloscope tracing of a sound wave produced by a musical instrument can identify the instrument, a voiceprint can be used to identify a person's voice. Using what you learned in the reading, Overtones, name two characteristics of people's voices that might cause them to have different voiceprints and explain how each characteristic would effect the sound produced.

INVESTIGATION 36: HARMONICS

MUSICAL SCALES*

Musical Scales

The origin of music is obscured by the lack of history of the early development of mankind; but as early as six centuries B.C., Pythagoras knew the simple mathematical ratios of the diatonic scale; there is some likelihood that he obtained the information from Egypt or India. Music has been developed by various races of people with differences in many respects, but with certain fundamental relations common to all.

Musical Intervals

Two pure tones are harmonious and pleasing to the ear if the ratio of their frequencies is made up of small numbers. The simplest ratio is 1:1, so that the two tones of the same frequency furnish the most harmonious combination. The next simplest ratio is 1:2, or the octave, and it is well known that two tones an octave apart are pleasing. The most important consonant intervals within an octave and their ratios to the lowest tone are as follows:

unison	1:1	major third	5:4
octave	2:1	minor third	6:5
fifth	3:2	minor sixth	8:5
fourth	4:3	major sixth	5:3

These intervals are recognized whatever the absolute frequencies may happen to be. For example, unison occurs if the two tones both have frequencies of 500 vibrations per second, or 600, or 1000, etc.: the fifth may have the ratio 200:200 or 600:400, etc.

Diatonic Scale

The so-called diatonic musical scale (The American Standards Association approved the name Just Scale for the Diatonic Scale, June 20, 1935) is made up of a series of tones that have a simple ratio to the tonic or lowest tone of the scale. For example, taking the scale of C, and calling the frequency of C the lowest tone 1, the ratios of the other tones in the scale are:

INVESTIGATION 36: HARMONICS

Table I

Ratios of Tones in the Diatonic Scale

	C	D	E	F	G	A	B	C′
Ratio of tone to C......	1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2
Ratio between successive tones	$\frac{9}{8}$	$\frac{10}{9}$	$\frac{16}{15}$	$\frac{9}{8}$	$\frac{10}{9}$	$\frac{9}{8}$	$\frac{16}{15}$	

It is seen that the tones E:C have the ratio 5:4, which is a major third, so that E is the third tone in the scale of which C is the first; F:C have the ratio 4:3, or the fourth, so that F is the fourth tone in the scale; C′:C have 2:1 or the octave, and C′ is the eighth tone. Some of the intervals are made up of ratios of larger numbers, such as D:C, with ratio 9/8, and the ratio B:C with the ratio 15/8, but these intervals are not so pleasing to the ear as the intervals of smaller numbers.

There are three different ratios between adjacent tones, namely: 9/8 between D and C, G and F, B and A; 10/9 between E and d, A and G; 16/15 between F and E, C′ and B. Inspection of Table II shows that the major tone ratio (1.125) and the minor tone ratio (1.111) are nearly equal, and that squaring the limma gives the ratio (1.138), which differs but little from the major and minor tone ratios. Hence the major and minor tones are called whole tones and the limma is called a half tone.

Table II

RELATION BETWEEN WHOLE TONES AND HALF TONE

Ratio	$\frac{9}{8}$ (major tone)	= 1.125
	$\frac{10}{9}$ (minor tone)	= 1.111
	$\frac{16}{15}$ (limma)	= 1.067
	$(\frac{16}{15})^2$	= 1.138

Table III displays two scales that accord with the natural, or diatonic, scale. One is the scale used by physicists, with the tonic C having a frequency of 256 cycles per second; the other is the one used by musicians, for which the tonic is 264, and the standard A frequency is 440 cycles per second.

Table III

FREQUENCIES OF SCALES USED BY PHYSICISTS AND MUSICIANS

	C	D	E	F	G	A	B	C′
Physicists	256	288	320	341	384	427	480	512
Musicians	264	297	330	352	396	440	495	528

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INVESTIGATION 36: HARMONICS

The different frequencies in the scales are obtained by calculation, using the ratios of Table I. Thus the tone D, 233, is 9/8x256; the tone E, 320, is 5/4x256, etc.

Major Scale

If Table I is rewritten with whole numbers instead of fractions, the values are shown in Table IV as 24, 27, 30, etc., by which the ratio of D:C is 27:24 or 9:8, and the ratio E:C is 30:24 or 5:4, etc. Examination of these numbers reveals some interesting relations, as in Table IV.

Table IV

MAJOR TRIADS IN A DIATONIC SCALE

C	D	E	F	G	A	B	C'	D'
24	27	30	32	36	40	45	48	54
4		5		6				
			4		5		6	
				4		5		6

Taking the tones C:E:G, the relative frequencies are 24:30:36, which, divided by 6, give 4:5:6--a major triad. In the same way, it is seen that F:A:C and G:B:D' constitute major triads. The diatonic scale is thus made up of major triads, and is called the major scale.

Minor Scale

The minor scale is made up of minor triads, which have the frequencies 10:12:15. These frequencies look entirely different from the major triad frequencies 4:5:6; and it might be concluded that the two triads are entirely unrelated. But if the major triad ratios are multiplied by 5 and the minor triad ratios by 2:

Major triad: (4:5:6)x5=20:25:30

Minor triad: (10:12:15)x2=20:24:30

they look very much alike. To convert a major triad to a minor triad, it is only necessary to flat the middle tone so that its frequency is reduced in the ratio 25:14. If the major scale above has the tones E, A, and B flatted, a minor scale is obtained.

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INVESTIGATION 36: HARMONICS

Equally Tempered Scale

Unfortunately the simple major scale and the minor scale do not suffice for the practical production of music. A soloist may not be able to sing as low as the tonic tone C and must start with D as the tonic. The tones in the C scale now do not give the necessary frequencies. For example, consider the frequencies of the notes given in Table V, where the tonic note C is 264 cycles per second; D is 264x9/8=297; E is 264x5/4=330,etc., and the octave is 264x2=528. Suppose now that a singer wants to use the note D (297) as the tonic instead of C (264). The next tone in the D scale is 9/8x297=334, which is not the same as the tone E (330) in the C scale. Therefore it would be necessary to supply an additional tone in the C scale. In the same way, the third tone in the D scale would be 5/4x297=371, which does not agree with the tone F (352), so that another tone should be added to the C scale. The next tone in the D scale is 4/3x297=396, which agrees with the tone G (396). Comparison of the other tones in the D scale, Table V, shows that a number of tones would have to be added to the C scale. But this is not all. If the E scale is selected as best suited to certain music, there would be other tones needed in addition to those already described. In a piano, it would mean the addition of a considerable number of keys, and would make the instrument unwieldy and more difficult to play.

Table V

NOTES IN DIATONIC SCALES DO NOT COINCIDE

	C	D	E	F	G	A	B	C'
	1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2
Key of C	264	297	330	352	396	440	495	528
		1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$
Key of D		297	334	371	396	445	495	557

This problem has been solved by several modifications of the natural, or diatonic, scale, called temperament but only the equally tempered scale is discussed here, since it is the one in common use. What is done is to keep the octave 2:1 unchanged as in the natural scale, then to insert five additional tones in the natural scale, and to make the 12 intervals thus obtained all equal. The five additional tones, C#, D#, F#, G#, A#, Figure 1, correspond to the black keys on the piano. Thus the first additional tone is C# or(Db). The second is D# (or Eb), etc.

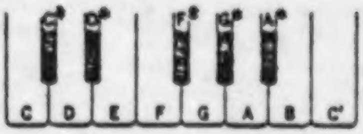

Figure 1. Additional notes in the equally tempered scale

Comparison between the Tempered Scale and the Diatonic Scale

To compare the equally tempered scale with the natural scale, it is first necessary to determine the interval of one of the tones of the equally tempered scale; and this requires some preliminary calculations. In the diatonic scale, Table IV , suppose that the frequency ratio E:C is to be calculated, having given the ratios D:C=27/24 and E:D=30/27. By multiplying the two latter ratios, 30/27x27/24, the ratio 30/24 is obtained, which is the desired ratio E:C. In the same way, the ratio F:C may be found by multiplying the ratios F:ExE:DxD:C or 32/30x30/27x27/24, giving 32:24 or F:C. Thus, the ratio of frequencies of any two tones in a musical scale is obtained by multiplying together all the ratios of the tones between the two tones. For example, in the equally tempered scale, calling the ratio between two adjacent tones x, such as C#:C, D:C#, etc., the ratio of the octave (2:1) is found by multiplying x by itself twelve times since there are twelve equal steps from C to C', so that:

$$x \cdot x \cdot x \cdot x \cdot x \cdot x \cdot x \cdot x \cdot x \cdot x \cdot x \cdot x = x^{12} = 2/1$$

from which $x = 2^{1/12} = 1.059$.

In the natural diatonic scale, the values of the whole tone ratio 9/8=1.125, and 10/9=1.111, so that the frequency ratio of the equally tempered whole tone, equal to $(1.059)^2 = 1.22$, lies between these values. Further, the natural half tone, 16/15=1.067, is nearly equal to the equally tempered half tone (1.059). It is thus seen that the equally tempered interval is a close approximation to the intervals of the natural diatonic scale. Table VI allows a comparison of the two scales to be made. The differences between the tones are small, being only 3.9 cycles per second as a maximum for the tone A, so that the equally tempered scale has come into common use as a

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compromise, although many bitter controversies have arisen during the process of adoption. With this scale, it is possible to use any tone as the tonic, remembering the 5 additional tones shown in Figure 1. Although it seems necessary to use this scale on the piano and organ because of the fixed tones, the natural scale is unconsciously followed when music is created by the voice, violin, and other instruments where the various frequencies are not fixed.

Table VI

COMPARISON OF DIATONIC AND EQUALLY TEMPERED SCALES

Scale	C	D	E	F	G	A	B	C'
Natural diatonic..........	264	297	330	352	396	440	495	528
Equally tempered	264	296.3	332.6	352.3	395.5	443.9	498.3	528
Difference in frequencies	0	0.7	2.6	0.3	0.5	3.9	3.3	0

Consonance and Dissonance in an Octave

The lack of harmony between two tones was explained by Helmholtz as due to the beats set up. That is, the effect of beats on the ear is much the same as the flicker of light on the eye. Passing a picket fence with flashes of light coming through is very unpleasant to the eye, but if the number of flashes per second increases beyond a certain number, the unpleasantness disappears. Helmholtz found a maximum unpleasantness between two sounds with about 33 beats per second in the neighborhood of a tone of 256 cycles per second; but he found a different value at other frequencies.

The harmony or discord between the tone C and other tones in an octave is shown in Figure 2, which illustrates the experimental results obtained by Helmholtz. For example, if the tone C is sounded with a second, similar tone slightly higher than C, say C#, a marked rise in discord follows. As the frequency of the second tone is increased, the discord becomes less until it disappears at the tone F, producing harmony. As the tone frequency increases, the discord fluctuates, becoming again zero at G, but rises rapidly again as the second note approaches the octave, but gives harmony at the octave.

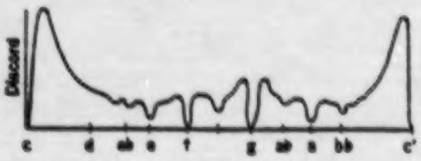

Figure 2. Helmholtz's diagram showing amount of discord between the tone C and the other tones of the scale. Zero discord indicates harmony. (From Barton's Text-book of Sound, courtesy of the Macmillan Company of New York and London.)

Consonance and Dissonance of Complex Tones

Suppose a vibrating string A has a fundamental tone of 100 cycles per second, and overtones of 200, 300, 400, and 500 cycles per second. No discord would result because between the fundamental and the first overtone there would be 100 beats per second which would harmonize with the fundamental. Any combination of fundamental and overtones would give 100, 200, 300, or 400 beats per second, any of which harmonizes with the other tones. Suppose, however, a second string B similar to string A is slightly mistuned to give a fundamental of 110 cycles per second and overtones of 220, 330, 440, 550. The beats set up in this case would be unpleasant.

Table VII

Beats with Mistuned Tones

	Fundamental	Overtones			
String A	100	200	300	400	500
String B	110	220	330	440	550
Beats	10	20	30	40	50

Compared with Helmholtz's plot in Figure 1, the two fundamentals would be in discord; the fundamental of A with the first overtone of B would give 120 beats that produce further discord with the 100 fundamental of A, etc. Consonance may thus be said to exist between two tones (including complex tones with overtones) that do not give beats as indicated by Helmholtz's diagram (Figure 2), but that do give objectionable beats with a slight mistuning.

Vibrato and Tremolo

In artistic singing and in playing some musical instruments, a sustained tone if fluctuated in a particular way, produces what is called a vibrato. Investigation of this phenomenon by recording the sound and analyzing it shows a fairly regular variation from a central mean about 6 or 7 times a second with small changes in frequency, intensity and tone-structure. The vibrato is regarded as an essential characteristic of good singing, but its full significance is only at present being understood. For the tremolo, on the other hand, the fluctuations are more rapid and are of greater magnitude than for the vibrato; it is not regarded favorably by musicians.

Since the appreciation of music depends on the ear, a knowledge of its performance becomes of fundamental importance. For example, it is shown that the estimation of the pitch of a loud sound depends on frequency, intensity, and tone-structure, so that the pitch of a loud sound is usually not numerically the same as the frequency. Physicists, musicians, and physiologists are now cooperating to determine the facts regarding music and hearing.

MUSICAL SOUNDS AND MUSICAL INSTRUMENTS

Noise and Music

A noise is usually thought of as disagreeable--it may be loud, sudden startling, and of short duration; music, on the other hand, is regarded as a pleasing combination of sounds that continue with regularity for some time. Perhaps a more accurate statement is that noise is any unwanted sound, and may include music at times. The distinction between noise and music is not always sharp. For example, if one of the sticks pictured in Figure 3 is dropped on a table, a noise will result; but if the eight sticks are dropped one after the other, they will give the simple musical scale.

INVESTIGATION 36: HARMONICS

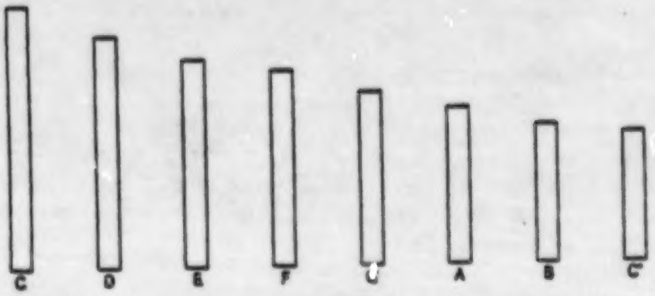

Figure 3. Series of sticks that give the musical scale

Characteristics of a Musical Sound

Investigations show that a musical sound has three characteristics: frequency, or the number of cycles per second of the fundamental of the sound; intensity, which is measured by the energy of the sound; and tone-structure, which is determined by the pure tones and their overtones present in the sound. These physical quantities are not what the ear distinguishes. Fletcher points out that pitch, as perceived by the ear, depends not only on the number of cycles per second, but also on the intensity and tone-structure, and that the loudness and quality are also dependent on all three objective physical characteristics.

Musical Instruments

Musical tones varying widely in frequency, intensity, and tone-structure are made possible by the large variety of musical instruments. Generally speaking, these instruments may be classified according to their methods of producing tones, i.e., by vibrating solids, vibrating air columns, or a combination of these two. Vibrating solids utilized in musical instruments include the strings of the violin, guitar, banjo, etc.; the rods and the cylinders of chimes; the plates of cymbals; the membranes of drums; and the curved plates of bells. Vibrating air columns are found in organ pipes, woodwind instruments, and brasses. Some instruments combine the two vibrators; for example, in reed organ pipes the solid reed generates the sound, but the vibrating air in the pipe magnifies it. The performance of any musical composition requires the selection of an instrument, or group of instruments, that has suitable characteristics regarding frequency range, intensity, and tone-structure.

Frequency Range of Instruments

Musical instruments taken together cover a wide range of frequency, although some of them are confined to a rather small portion of the scale. Figure 4 (Musical Scales) shows the ranges of frequency that are to be expected of various instruments, for which the musical score is written. For instance, the violin has its lowest tone fixed by the bass string as G, or a frequency of 192 cycles per second, by using the upper part of the E string. The piano has the widest range, from A with 26.67 cycles per second to C with 8,192 cycles per second.

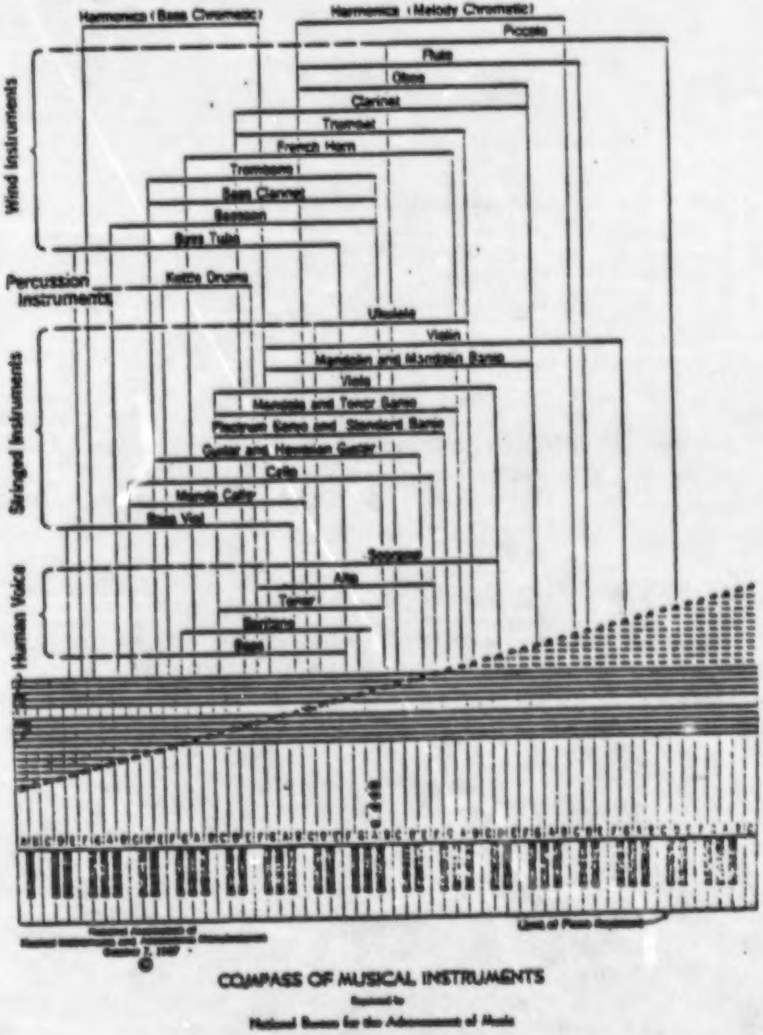

Figure 4. Frequency ranges for musical instruments. (Reprinted by permission of the two national organizations indicated in the figure.)

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The ranges indicated in Figure 4 are smaller than the actual range of tones obtained when instruments are played because they include only the fundamental tones without the usual overtones. Figure 5 pictures the actual ranges of frequency of musical instruments determined experimentally at the Bell Telephone Laboratories, and it will be noted that the tones extend from 40 cycles per second with the bass viol, to 15,000 cycles per second with the snare drum and oboe. The instruments were played by professional musicians who were instructed to play loud to get the widest frequency range. The upper and lower limits of the ranges were determined by eleven young observers with normal hearing.

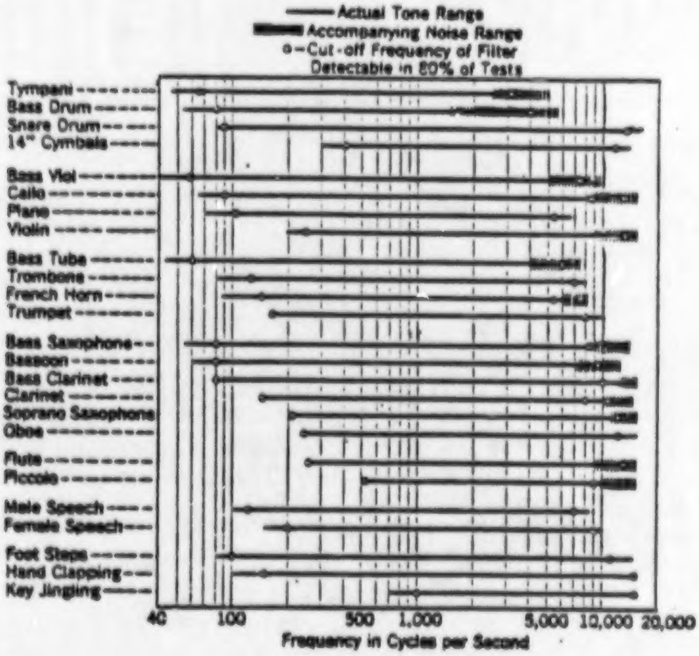

Figure 5. Frequency ranges for musical instruments. (W. B. Snow, Journ. Acoustical Soc., July, 1931.)

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Consider, for example, the results for the cello. The lowest frequency of 65 cycles per second at the left end of the solid line was correctly judged in 60 percent of the observations, while 90 cycles per second, shown by the circle, was correctly judged in 80 percent of the tests. At the right end of the line the circle at 8,500 cycles per second was correctly judged in 80 percent of the tests, so that the region between the circles is most significant, although some observers heard tones above and below these limits. With most instruments it was noticed that the actual musical sounds were accompanied by other sounds such as key clicks, lip noises, buzz of reeds, and hissing of air, which are shown in the figure by the short vertical lines. These noises are all at the upper end of the frequency range, and in some cases the noise and tone seemed inseparably blended.

Intensity of Musical Instruments

A second characteristic of musical instruments is the power of the sound they emit. The trombone, for example, is much more powerful in its performance than the violin. It is therefore necessary to choose the instruments in an orchestra that will give the proper balance of intensity. Values of the powers of various musical instruments have been determined by tests at the Bell Telephone Laboratories, as given in Table VI.

Table VI*

Instrument	Peak Power in Watts
Heavy orchestra	70.0
Large bass drum	25.0
Pipe organ	13.0
Snare drum	12.0
Cymbals	10.0
Trombone	6.0
Piano	0.4
Trumpet	0.3
Bass saxophone	0.3
Bass tuba	0.2
Bass viol	0.16
Piccolo	0.08
Flute	0.06
Clarinet	0.05
French horn	0.05
Triangle	0.05

* Peak power of musical instruments (Fortissimo playing) (Sivian, Dunn and White, Journ. Acous. Soc. of Am., Jan., 1931).

INVESTIGATION 36: HARMONICS

The plan followed in the tests was to have a professional musician play a selection representative of his instrument, usually including extremes of range and volume, and different types of playing. Selections were made at least two minutes long, so that four average amplitude readings and at least 480 peak amplitude reading over the range of frequency were obtained. The sound was picked up by a condenser microphone and passed through an electric network to a meter to measure the various elements.

Inspection of Table VI shows the relative powers of the various instruments, ranging from 70 watts for a heavy orchestra of 75 pieces through various single instruments down to 0.05 watt for a triangle. The values recorded in Table VI are peak powers. When the heavy orchestra played four different selections, the maximum peak powers ranged from 8 to 66 watts, but the average powers were 0.08, 0.07, 0.07, and 0.13 watt, respectively.

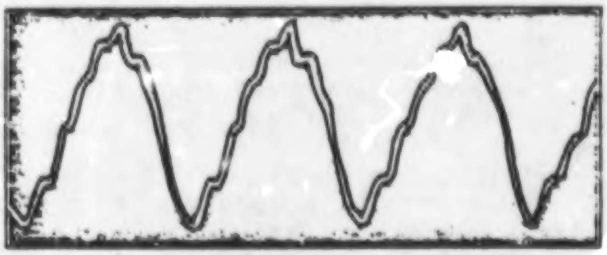

Figure 6. Photograph of the tone of a violin, frequency=290 cycles per second. (Courtesy of D. C. Miller, Science of Musical Sounds.)

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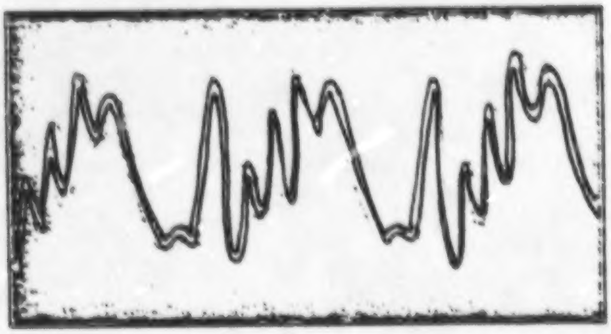

Figure 7. Photograph of the tone of an oboe, frequency=256 cycles per second. (Courtesy of D. C. Miller, Science of Musical Sounds.)

Hence the variation of the average power from selection to selection was much less than that of the peak power. Measurements were not taken for weaker sounds, excepting one test in which a violin was played at the lowest level used with an audience. The result gave 0.0000038 watt, showing that the range of intensity of sounds in an orchestra is very large--from 0.0000038 to 70 watts, so that the sound of the orchestra was about 20,000,000 times more intense than that of the softly played violin.

Quality of Sounds from Musical Instruments

An oboe and a violin even when emitting a tone of the same frequency and intensity sound quite different. When the sounds from these instruments are recorded, they are found to differ in quality; that is, they have different components. Thus Figure 6 shows the simple form of the violin tone, while Figure 7 shows the more complex sound from the oboe. Sounds from other instruments show different degrees of complexity. To compare these sounds, use is made of a theorem developed by Fourier.

Fourier's Theorem

It is interesting to learn, as explained by Fourier, that any complex sound is made up of a number of pure tones, that is, of simple harmonic components.

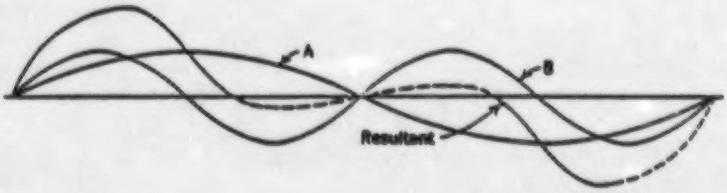

Figure 8. A complex tone made up of two components

For example, consider the simple case where the resultant tone is made up of two tones, as shown in Figure 8, which shows how two components A and B whose wave-lengths are in the ratio 2:1 produce a resultant that is obtained by the addition of their displacements at each point. Inspection of the complexity of the curve for the oboe tone in Figure 7 makes one wonder what the components might be.

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* Taken from Floyd Rowe Watson, Sound, (New York: John Wiley and Sons, Inc., 1935), pp. 107-123